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RESEARCH ARTICLE

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Variable length dynamic addressing based on network traffic distribution in wireless sensor networks

Abstract In this paper, a novel dynamic addressing scheme for wireless sensor networks (WSNs) is proposed by using variable length coding. A WSN is typically composed of numerous tiny energy-constrained sensor nodes with limited information processing and data storage capabilities; thus, the energy-efficient strategy is the key issue in designing protocols for WSN. Traditional addressing strategies adopt flat addressing (static and uniform addresses) for sensor nodes. However, the proposed variable length dynamic addressing (VLDA) for sensor nodes is based on the fact that different nodes in the network have uneven traffic loads. Therefore, nodes with more data to receive or send are allocated with shorter addresses. Whether a node is busy or not is determined by the network traffic distribution (NTD), which is defined as the number of data packets each node has received or sent in a period of time. Sensor nodes' energy is saved by VLDA scheme; hence, the wireless sensor network's lifetime is extended. In the simulation, a 20% improvement has been achieved through the addressing scheme compared to traditional flat addressing.

Keywords variable length dynamic addressing (VLDA), wireless sensor network (WSN), energy saving, network traffic distribution (NTD)

1 Introduction

Wireless sensor networks (WSNs) are spontaneous networks, and have become the interface to the physical world, gathering ambient conditions for scientific, military, and civil intentions, particularly in some regions where man can hardly approach. When certain ambient condition changes or some events the sensor nodes are concerned with happen, the data will be transmitted to gateways or some powerful devices that are capable of storing and further processing the information. WSNs are expected to achieve desired applications without any external interventions. Communications are enabled in an ad hoc fashion using low-power wireless communication technologies such as IEEE 802.15.4 [1]. Sensor nodes are massively produced identically, and some of them have an identifier like a media access control (MAC) address while some of them do not. However, to guarantee the correct data transmission in the network, each node should have a unique identifier. Therefore, it is necessary to provide a scalable, energy-saving and distributed dynamic address allocation scheme that ensures the smooth running of the self-adaptive network. Unfortunately, traditional static and uniform addressing is not flexible enough, and cannot adjust appropriately in the event of some changes in the network.

Sensor nodes are deployed randomly and unattended; hence, the traffic loads in different areas are not the same. Nodes with more data to receive or send are named busy nodes, while those with less data to receive or send are called idle nodes. Whether a node is busy or not can be deduced from their traffic loads. In general, variable length dynamic addressing (VLDA) assigns shorter addresses to busy nodes, and longer addresses to idle nodes. Busy nodes can have shorter addresses when adopting variable length dynamic addressing-network traffic distribution (VLDA-NTD); therefore, the control sections including originator and destination addresses become lightweight and efficient for data transmission. Consequently, the lifespan of the WSN is prolonged.

The rest of this paper is organized as follows. In Sect. 2, we review some related researches in the area of addressing strategies and variable coding. The proposed VLDA-NTD is described in Sect. 3. Simulations are shown in Sect. 4. Finally, we give concluding remarks in Sect. 5.

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2 Related works

VLDA-NTD is a novel integrated addressing scheme using variable length coding. In this section, two related aspects are introduced respectively.

2.1 Addressing schemes

Network addressing schemes are usually defined with a fixed length field for addresses, and some techniques are introduced to ensure the uniqueness of addresses. In general, addressing schemes can be classified into stateless and stateful ones.

Stateless schemes allow the nodes to form own addresses based on their local identifications (IDs), such as MAC addresses. However, stateless addressing cannot ensure the uniqueness of the addresses. Even auto-configured Internet protocol version 6 (IPv6) addresses, which are usually based on hardware IDs, are not necessarily unique. Thus, some techniques such as duplicate address detection (DAD) are needed to check the uniqueness of addresses. Moreover, sensor nodes are recommended to be produced identically from a massive production in order to attain a low cost; thus, nodes may not have identifiers like MAC addresses, and this makes stateless auto-configuration infeasible.

Stateful schemes do not have the above problems, and a popular stateful scheme is dynamic host configuration protocol (DHCP) [2], which establishes an IP host system. However, DHCP suffers from heavy control message overhead. Specifically, a periodical 1-hop hello message is used to maintain address information among nodes in distributed DHCP, which leads to a huge energy consumption.

Internet protocol version 4 (IPv4) [3] and IPv6 [4] are integrated with WSN in recent researches, and sensor nodes are assigned with IP addresses. The length of IPv4 address is 32 bit while IPv6 expands the address space to 128 bit. Long address is positive for ensuring the uniqueness of addresses; however, it is inefficient for energy-constrained sensor networks. IPv6 over low power wireless personal area networks (6LowPAN) [5,6] is an Internet Engineering Task Force (IETF) standardization effort providing networking over IEEE 802.15.4 networks. A sensor node in 6LowPAN has an IPv6 address, which is formed with interface ID based on either IEEE 16-bit short address or globally unique 64-bit extended unique identifier (EUI) address. IP communication overhead has been significantly reduced by 6LowPAN. However, there is still room for improvement.

2.2 Variable length coding (VLC)

VLC, best represented by Huffman coding, is an entropy encoding algorithm used for lossless data compression. VLC, developed by David A. Huffman in 1952 [7], refers to the use of a variable-length code table for encoding a source symbol where the code table has been derived in a particular way based on the estimated probability of occurrence for each possible value of the source symbol. Huffman coding uses a specific method to choose the representation for each symbol, resulting in a prefix code (also called prefix-free code) which expresses the most common characters using shorter strings of bits than are used for less common source symbols. Taking text compression as an example, character ‘a’ and ‘e’ may occur frequently, so they may be encoded as 00 and 01, while ‘z’ and ‘q’ may be encoded as 10100 and 10101.

3 VLDA-NTD description

In this section, we offer a detailed description of VLDA-NTD scheme. An example of VLDA-NTD is given, and VLDA-NTD is proved to be the optimal addressing scheme in most WSNs.

Traffic loads in sensor networks are usually proportional to the density of sensor nodes, which means traffic is busier in dense areas. This traffic distribution stays stable unless some changes occur including joining or departure of large quantity of nodes. Another situation is some key nodes are always busier than others because of their location in the network, and this is also a stable situation except that the network topology changes sharply. The stable traffic distribution guarantees the satisfactory performance of VLDA-NTD scheme, and VLDA-NTD is also competent to handle general network changes.

The coding algorithm we use to compute the addresses is VLDA, which is an extension of Huffman coding for arbitrary weights. The weight in VLDA is not estimated probability of occurrence, but NTD. An example of how to generate the addresses based on NTD is given below.

A set of sensor nodes $\{N_1,N_2,\ldots,N_8\}$ forms a WSN. At the initialization phase, the gateway assigns addresses with the same length. Therefore, a 3-bit address is assigned to each node. If the total number of nodes n satisfies $2^{m-1} < n \leqslant 2^m$, m bit is needed. As shown in Fig. 1, nodes have address {000,001,…,111} respectively. After a constant time T which is defined as a cycle, the gateway computes each node’s packet percentage in this cycle, and assigns new addresses to them. For example, in cycle T_1, data packets received and sent by node N_1 and N_2 are both 4, so $D(1)=D(2)=4$. Similarly, $D(3)=D(4)=2$, and $D(5)=D(6)=D(7)=D(8)=1$. Therefore, the total packets in the network during cycle T_1 is 16, namely $S_1=16$. Now, each node’s packet percentage in the network’s total packets in cycle T_1 can be computed. N_1 receives four data packets in T_1; therefore, its packet percentage $P_1(1)=4/16=0.25$. Similarly, we have $P_1(2)=0.25$, $P_1(3)=P_1(4)=0.125$, $P_1(5)=P_1(6)=P_1(7)=P_1(8)=0.0625$. According to these percentages, a binary tree can be easily built as Fig. 2, and

N_1 and N_2 which have the busiest traffic in the network during T_1 own the shortest address 00 and 01. N_3 and N_4 have the 3-bit address 100 and 101. 1100, 1101, 1110 and 1111 are assigned to N_5 to N_8. Notice that N_5 to N_8 have longer addresses compared with what they have in Fig. 1, which is the nature of variable length addressing.

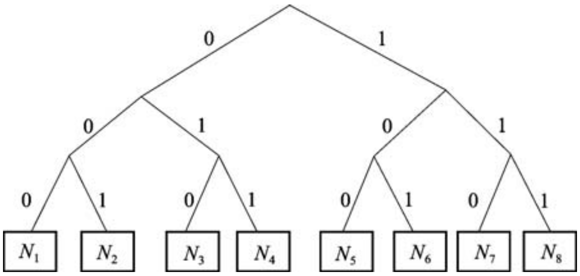

Fig. 1 Address allocation at initialization phase

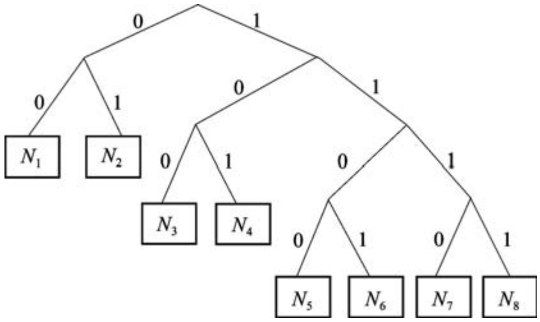

Fig. 2 Address allocation after a period of time

From the above example, it can be seen that the sensor nodes are treated as a discrete memoryless source with source statistics $P = (p_0,p_1,...,p_{r-1})$, satisfying $\sum_{i=0}^{r-1} p_i = 1$. Addresses are regarded as binary codes encoded for the source. Addresses should be uniquely decodable (UD); hence, the binary codes must be UD codes. Furthermore, there is a special class of UD codes called prefix codes, which will be sufficient for our purpose. A code C is called a prefix code if no codeword is a prefix of any other. Prefix codes are necessarily UD, but the converse is not true. For example, code $C_1 = \{0, 01, 11, 111\}$ is not UD, and we cannot use it as sensor nodes' addresses. If the address section is 0111, it is possible to have originator address 0 and destination address 111, or 01 as originator address and 11 as destination address. Code $C_2 = \{0, 01\}$ is UD in spite of the fact that 0 is a prefix of 01. The codes built in Fig. 2 are not only UD codes, but also prefix codes.

Whether this VLDA scheme saves energy or not depends on the average length of the encoded address codes; hence, we are searching for the smallest possible average length for a UD binary code. As defined in information theory, the entropy of a discrete source is

$$H(p) = -\sum_{i=0}^{r-1} p_i \log_2 p_i. \tag{1}$$

If C is UD, its average length n has following useful estimation:

$$H(p) \leqslant n \leqslant H(p) + 1. \tag{2}$$

For a detailed proof, please refer to Ref. [8]. The entropy of the example in Fig. 2 is 2.75, and the average length of the codes is also 2.75. This is a lucky result, since not every time can it be achieved. The preceding of this example is typical of general Huffman algorithm: P is successively reduced until a final reduction with exactly two statistic numbers is reached. The obvious optimal code {0,1} is then "expand" in the above way until an optimal code for P is obtained. Theoretically, this algorithm guarantees that there is always an optimal prefix code for P. "Optimal" means a code of minimal average length. Therefore, the optimal prefix code for P has a smaller average length n than any other UD codes [8]. That is

$$n = \min_{\sum_{i=0}^{r-1} 2^{-n_i} \leqslant 1} \sum_{i=0}^{r-1} p_i n_i. \tag{3}$$

Hereby, the addresses generated by VLDA-NTD are proved to have the smallest average length based on the traffic distribution of the previous cycle, and sensor nodes' addresses are prefix codes; thus, no other control section related to addresses is necessary. If the traffic distribution in cycle i is proportional to that in cycle $i-1$, the ideal performance of VLDA-NTD can be reached. As shown in Fig. 2, N_1 and N_2 have the shortest addresses based on NTD in cycle T_1, while N_5 to N_8 have the longest ones. In cycle T_2, if any sensor nodes among N_5 to N_8 suddenly become the busiest, VLDA-NTD will not perform well and will even consume more energy in cycle T_2. However, this is also a feature of dynamic addressing. When the traffic distribution alters, the network can adjust nodes' addresses accordingly. Therefore, the network will be appropriate for the traffic distribution in following cycles. But as mentioned in the beginning of Sect. 3, the traffic distribution is not likely to alter dramatically, which is still the promise of ideal performance of VLDA-NTD.

Seen from the above analysis, how much energy can be saved by VLDA-NTD somewhat depends on NTD. If the network traffic mainly concentrates in a small area or on several key nodes, the effect of VLDA-NTD will be excellent, because the addressing scheme assigns shorter addresses to these busy nodes, and energy is saved. This occasion is of high probability. Sensor nodes are randomly distributed, and the network's topology is usually unsystematic; therefore, some regions with denser nodes have more traffic loads than those with sparser nodes, and some key nodes always having busier traffic is also possible. Compromisingly speaking, if the network traffic distribution is symmetrical and all the nodes have identical packet percentage P, which is the worst situation for VLDA-NTD, all the nodes will be assigned with addresses with the same length; therefore, VLDA-NTD is still as good as flat addressing.

The VLDA-NTD scheme is presented in detail above, and the only mysterious feature of this scheme is how to realize the “cycle”. We adopt a MAC protocol with listen-sleep schedule. The sleep period is the “cycle” in which sensor nodes receive and send data packets normally and the gateway computes their traffic loads. The listen period is a rather small period of time, used for the address updating. Figure 3 illustrates this listen-sleep cycle mechanism. In listen period, the gateway first informs the nodes with new addresses, and then these nodes will broadcast their new addresses. Several similar MAC protocols for WSN have been proposed, and sensor medium access control (S-MAC) [9] is the most well-known one which adopts a periodic listen-sleep cycle. Neighbor nodes in a subnet or a virtual cluster set up a common synchronized listen-sleep schedule. Timeout medium access control (T-MAC) [10] and differential service medium access control (DS-MAC) [11] enhance S-MAC by adding a dynamic duty circle feature, and they all adopt synchronized listen-sleep scheduling.

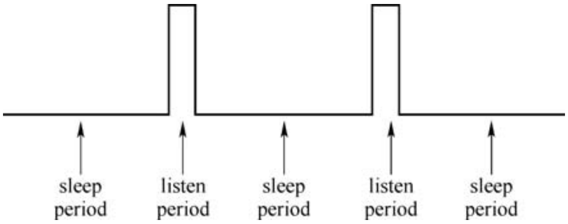

Fig. 3 Listen-sleep cycle

4 Simulation results

In this section, we compare the performance of VLDA-NTD with traditional flat addressing by using OPNET simulator. We have set up scenarios consisting of 200 immobile sensor nodes using S-MAC randomly distributed in the network, and a powerful gateway at the edge of the network. The gateway computes each node’s address based on NTD, and informs nodes of their new addresses during listen periods. If node A’s address is changed, it broadcasts address notification message (ANM) in its radio range, hence all 1-hop neighbors update A’s address in routing tables.

Our simulation simplifies the data packet structure. Two sections, the originator address and the destination address, form the packet header, and other control fields are neglected. This simplification will not affect the validity of the simulation result, because both the flat addressing scheme and VLDA-NTD have this simplification during simulation, and energy consumption caused by these control fields is insignificant compared with the energy cost by address fields. Besides the packet header, each packet has a 16-bit overload. Based on the rational assumptions, flat addressing needs 8 bit to form 200 unique addresses. Therefore, packets using flat addressing are 32 bit long, consisting of 8-bit originator address, 8-bit destination address and 16-bit overload, while addresses using VLDA-NTD would be shorter or longer than 32 bit. Moreover, 1 microjoule is depleted per transmission bit.

Four scenarios are designed:

1) Flat addressing;
2) VLDA-NTD with sleep period length of 1500 s;
3) VLDA-NTD with sleep period length of 1000 s;
4) VLDA-NTD with sleep period length of 500 s.

The only difference among the four scenarios is the sleep period length. Other parameters such as network topology and constant bit rate (CBR) are identical, and the listen period length is neglected because it is rather short. Now we define AP(t) as follows:

$$\mathrm{AP}(t) = \frac{\sum \frac{H(t)}{\mathrm{TL}(t)}}{\mathrm{Sum}(t)}, \tag{4}$$

where $H(t)$ means the header length of a data packet, TL(t) indicates the total length of the packet, and Sum(t) represents the total count of data packets existing in the network at time t. The smaller AP(t) is, the more lightweight the average packet header is and the more efficient the addressing scheme is. Figure 4 shows AP(t) of four scenarios. In Scenario 1, it is a static value of 0.5. For Scenarios 2 to 4, AP(t) becomes smaller than 0.5 after their first cycle. Although variable length address allocation makes some nodes’ address longer than 8 bit, the average length is smaller than flat addressing scheme.

Figure 5 shows total energy consumptions of four scenarios. It can be seen from Fig. 5 that scenarios applied with VLDA-NTD have over 20% energy saved compared with flat addressing. One thing must be emphasized is this energy saving is not brought by the listen-sleep schedule of S-MAC, but by VLDA-NTD; because nodes with more traffic loads have the shorter addresses. Another fact shown in Fig. 5 is that Scenario 4 with the smallest sleep period length (500 s) is the most efficient one; however, the difference among Scenarios 2 to 4 is not obvious. Consider that nodes with new addresses will broadcast ANMs every time their address is updated, the cycle length should not be too small to prevent generating too many ANMs frequently which also cost sensor nodes’ energy. Moreover, too small cycle length cannot reflect NTD. Therefore, the cycle length should be selected appropriately according to the concrete situation.

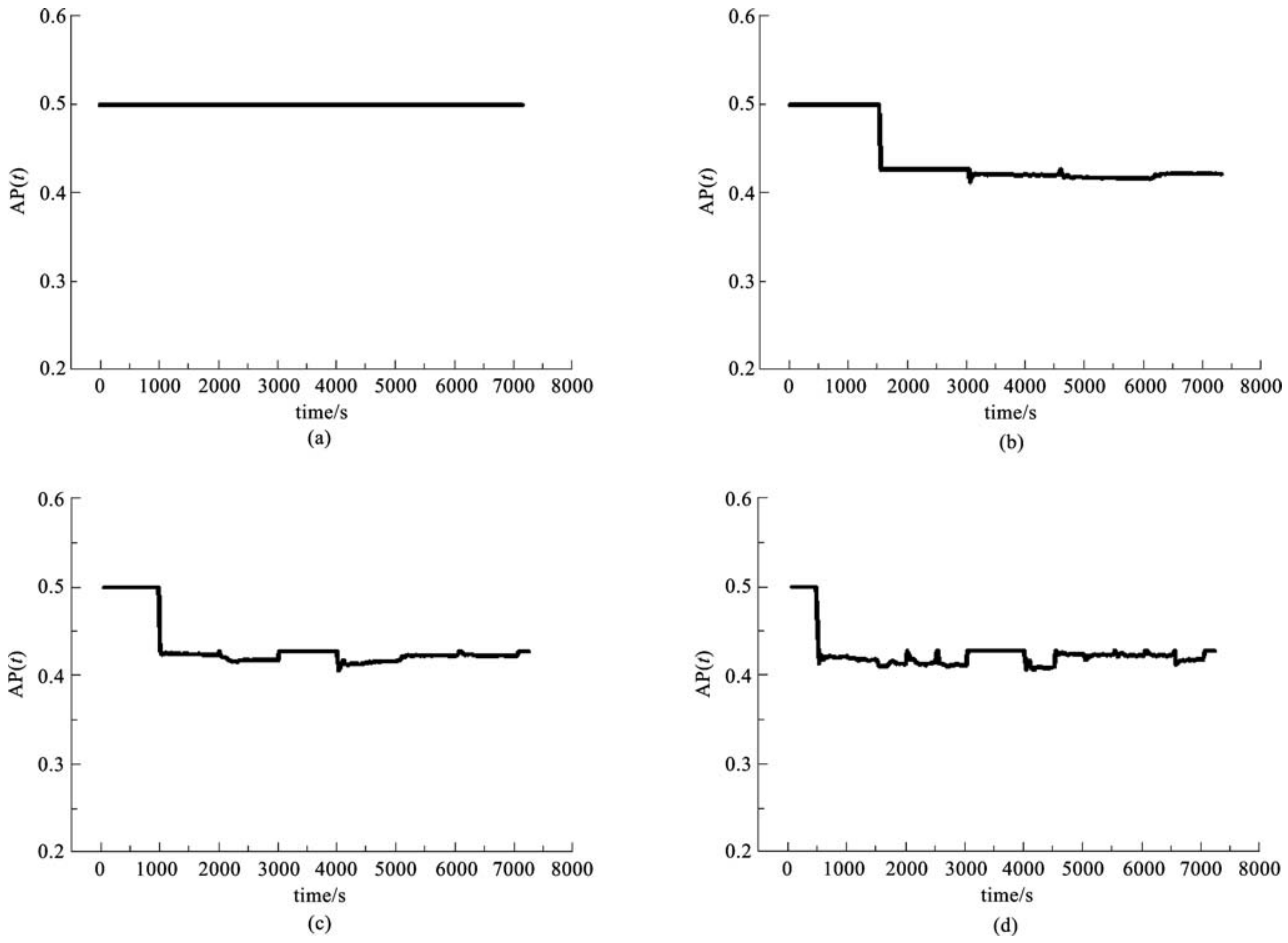

Fig. 4 AP(t) of four scenarios. (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4

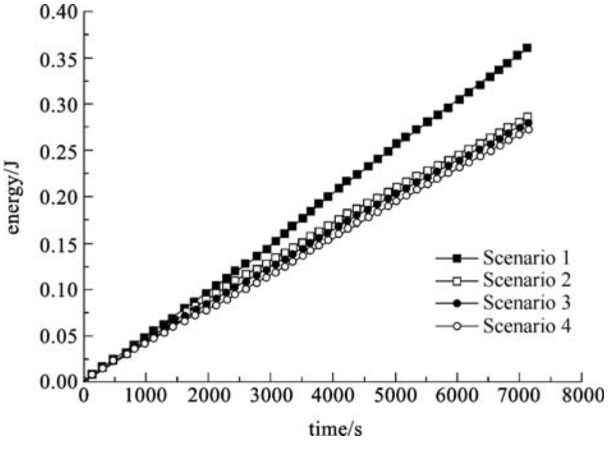

Fig. 5 Total energy consumptions of four scenarios

5 Conclusions

In this paper, we propose a novel addressing scheme VLDA-NTD, which represents a better performance in terms of energy consumption, thereby extending the lifespan of WSN. This scheme preserves nodes' energy by assigning shorter addresses to nodes with heavier traffic loads. Some synchronization techniques, such as listen-sleep cycle in S-MAC, can be used to cooperate with VLDA-NTD. In Sect. 4, we have compared VLDA-NTD with flat addressing; hence, the advantage of VLDA-NTD will be more significant if EUI-16 or EUI-64 addresses were used in the comparison. Also, VLDA-NTD is feasible in various types of sensor networks, even if sensor nodes have no unique identifiers like MAC addresses. VLDA-NTD is proved to be beneficial to energy-constrained networks, and can improve the sensor networks' lifetime.

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