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# A novel distributed algorithm for media access control address assignment in wireless sensor networks

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**Abstract** This paper presents a novel distributed media access control (MAC) address assignment algorithm, namely virtual grid spatial reusing (VGSR), for wireless sensor networks, which reduces the size of the MAC address efficiently on the basis of both the spatial reuse of MAC address and the mapping of geographical position. By adjusting the communication range of sensor nodes, VGSR algorithm can minimize the size of MAC address and meanwhile guarantee the connectivity of the sensor network. Theoretical analysis and experimental results show that VGSR algorithm is not only of low energy cost, but also scales well with the network size, with its performance superior to that of other existing algorithms.

**Keywords** wireless sensor networks, media access control (MAC) address, distributed, geographical position

## 1 Introduction

A wireless sensor network [1] is a new technical system for acquiring and processing information, where thousands or even millions of sensor nodes work together in an Ad-hoc fashion [2] and sense interested information from the surrounding areas. Due to the small size of sensor nodes, energy reserve on each node is extremely limited [1]. Considering that power recharge is unpractical, every node in a sensor network must raise the energy utilization rate so as to maximize the lifetime of the whole network. Compared with sensing and processing progresses, communication consumes a large part of energy [3], and the transmission of every bit will consume corresponding energy [4]. Therefore, to maximize the lifetime of this system, it is critical to minimize the number of bits in transmitted packets. As the payload of data decreases greatly after aggregation [4], the overhead

of the header becomes evident, where media access control (MAC) address occupies a relatively large proportion. Therefore, for energy saving, it is meaningful to reduce the size of MAC address.

To solve this problem, Schurgers et al. proposed a distributed algorithm to assign MAC address on-demand for sensor nodes [3,5]. By reusing limited address spatially, the algorithm can reduce the overhead of MAC address efficiently. However, the variable size of MAC addresses requires extra processing cost and the periodic broadcasting between neighboring nodes also leads to large energy consumption.

This paper presents a novel MAC address assignment algorithm virtual grid spatial reusing (VGSR) for wireless sensor networks. Based on the fact that MAC addresses should be unique in a local area, VGSR reuses MAC addresses in space and decreases the MAC address size greatly. Moreover, VGSR assigns MAC addresses with fixed length for nodes through the mapping of geographical position, which can reduce overhead of itself efficiently. All of these above contribute to the extension of the lifetime of sensor nodes ultimately.

## 2 MAC address reuse

In communication, the function of MAC addresses is to uniquely identify the given sender and receiver of data frames at each hop, which means that MAC addresses just need be unique within a local area. Thus, many sensor nodes located in different areas can reuse the same MAC address spatially. From now on, we will use the term “address” to denote the MAC address.

A sensor network composed of  $N$  nodes can be modeled as a simple graph  $G = (V, E)$ , where  $V$  and  $E$  represent the set of sensor nodes and wireless links of the network respectively. For any node  $i \in V$ , we define: neighboring set  $V_{nbr,i} = \{j | (j, i) \in E, i, j \in V\}$ , two-hop neighbor set  $V_{two\_hop,i} = \{j | (j, k) \in E, k \in V_{nbr,i}, j \notin V_{nbr,i}, i, j, k \in V, j \neq i\}$  and two-hop range node set  $V_{two\_range,i} = V_{nbr,i} \cup V_{two\_hop,i}$ .

**Lemma 1** For any node  $i, i \in V$ , all its neighbors as well as  $i$  must use addresses different from each other.

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**Proof** Suppose that  $A_x$  is node  $x$ 's address. For any node  $i$ , when  $i$  sends/receives a frame, it is necessary to uniquely identify a given receiver /sender from  $V_{nbr,i}$ . Therefore, for any node  $j$  and  $k$ ,  $j, k \in V_{nbr,i}$ ,  $A_j$  should be different from  $A_k$ . Besides, there should be  $A_i \neq A_j, j \in V_{nbr,i}$ . Thus, Lemma 1 holds.

**Lemma 2** For any node  $i, i \in V$  and  $A_i$  cannot be reused in the two-hop range of node  $i$ , while out of this range,  $A_i$  can be reused.

**Proof** According to the definition of two-hop neighboring nodes, for any node  $j, j \in V_{two\_hop,i}$  there must be a node  $k, k \in V_{nbr,i}$  that is a common neighbor of  $i$  and  $j$ . In other words, both  $i$  and  $j$  belong to  $V_{nbr,k}$ . Based on Lemma 1,  $A_i$  must be different from  $A_j$ . Thus,  $A_i$  cannot be reused in the two-hop range of node  $i$ . Assume  $j \notin V_{two\_range,i}$  then the distance between  $i$  and  $j$  is definitely larger than 2 hops. This means that  $i$  and  $j$  have no common neighbors, so that  $A_j$  can be equal to  $A_i$ . Hence, out of the two hop range of node  $i$ ,  $A_i$  can be reused. Therefore, Lemma 2 holds.

### 3 VGSR algorithm

The VGSR is a distributed algorithm on the basis of the geographical position, which efficiently assigns local unique MAC addresses with fixed size for sensor nodes. In VGSR, according to network scale, each sensor node will conceive a virtual grid including a series of virtual square cells for which spatially reused local unique identifiers are assigned. Then, every sensor node distributed randomly and uniformly maps its geographical position coordinates onto a unique cell and chooses the identifier of the cell (cell address) as its MAC address. After declaration, sensor nodes can use the MAC address without confliction. For convenience, VGSR is divided into four parts: construction of virtual grid, cell address assignment, address mapping and address collision resolving. Following that each of them is elaborated respectively.

#### 3.1 Construction of virtual grid

All sensor nodes are assumed to scatter uniformly in the whole distributing area after deployment. According to network scale, each sensor node conceives a virtual grid respectively and divides the distributing area into a series of small square areas called "virtual cells", as shown in Fig. 1. In VGSR, sensor nodes will choose the identifier of the cell as its MAC address. Thus, in order to avoid address collision, it is expected to make each cell contain only one sensor node.

**Theorem 1** In a network with an area of  $S_{area}$  and  $N$  nodes distributed uniformly, the side of a square cell that contains one node on average is

$$d = \sqrt{\frac{S_{area}}{N}} \quad (1)$$

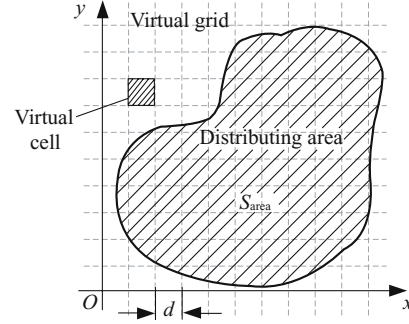


Fig. 1 Virtual grid and virtual cells

**Proof** Due to the uniform distribution of sensor nodes, the average number of nodes in a cell, denoted by  $n$ , just depends on average node density  $\rho$  and cell area  $S_{cell}$ , i.e.

$n = \rho S_{cell} = \frac{N}{S_{area}} d^2$ . When a cell contains only one node on average,  $n$  should equate to 1, and then Eq. (1) can be obtained.

#### 3.2 Cell address assignment

Before discussion, following definitions shall be given:

- reusing cell: the cells using the same address;
- reusing distance  $d_r$ : the distance between the centers of two adjacent reusing cells;
- address size  $b$ : the number of address bits;
- address space  $\Omega : |\Omega| = 2^b$ ;
- cell address  $A_{cell}$ : the set of addresses allocated to cells.
- spare address  $A_{spare}$ : the set of addresses unused by cells in address space.  $A_{spare} = \Omega - A_{cell}$ .
- cell cluster: the minimum unit consisting of a cluster of cells that use all addresses of  $A_{cell}$ .

As sensor nodes will choose the cell address that they belong to as their address, the assignment of address for the sensor nodes is actually equivalent to the address assignment for virtual cells. The communication range of sensor nodes is supposed to be  $R$ , then the distance between a pair of two-hop neighboring nodes is  $2R$  at most. According to Lemma 2, all the cells in the range of  $2R$  must have different addresses. The number of these cells jointly depends on  $R$  and  $d$ .

Figure 2(a) takes  $R = d$  as an example and shows the case that node  $i$  locates in a center of a cell. The barred cells are partly or completely covered by the  $2R$  range of  $i$  (represented by the outer circle). As a result, they must have addresses different from  $A$ . In order to reduce the number of cell addresses as many as possible, the four nearest cells (in gray) beyond the two-hop range are selected as reusing cells, as shown in Fig. 2(b). Therefore, the reusing distance  $d_r = 3d$ . All the other cells keeping a shorter distance from "A" cells than  $d_r$  must use distinct addresses, which can also be reused in the same way. All these cells as well as an "A" cell constitute a cell cluster (just as demonstrated by the dark frame), which includes nine virtual cells altogether.

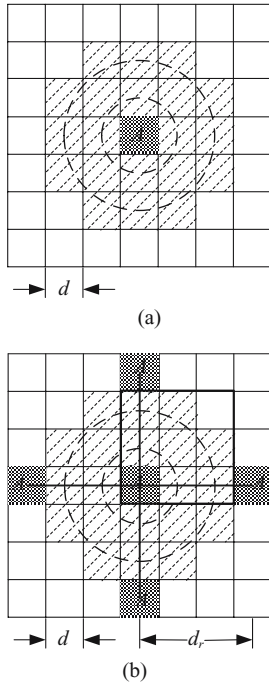


Fig. 2 Address spatial reuse

Generally, for any  $R$  and  $d$ , the reusing distance can be

$$d_r = \left( \text{Int} \left( \frac{2R}{d} \right) + 1 \right) d \quad (2)$$

where,  $\text{Int}(x)$  is the smallest integer greater than or equal to  $x$ . Each cell cluster contains  $(d_r/d)^2$  cells and needs  $|A_{\text{cell}}| = (d_r/d)^2$  addresses. If we define the average connectivity of one node as  $\lambda = (N/S_{\text{area}})\pi R^2$ , the bit number needed by the address can be expressed as

$$\begin{aligned} b^* &= \text{Int}(\log_2 |A_{\text{cell}}|) = \text{Int} \left( \log_2 \left( \frac{d_r}{d} \right)^2 \right) \\ &= \text{Int} \left( \log_2 \left( \text{Int} \left( 2\sqrt{\frac{\lambda}{\pi}} \right) + 1 \right)^2 \right) \end{aligned} \quad (3)$$

and the spare address  $|A_{\text{spare}}| = 2^{b^*} - |A_{\text{cell}}|$ . Spare addresses are remained addresses in address space, which prepare to resolve address collision (to be discussed in Sect. 2.4). In order to guarantee  $A_{\text{spare}} \neq \emptyset$ , in some cases one more bit is needed to set aside spare addresses, so the address size  $b$  adopted by VGSR actually is

$$b = \begin{cases} b^*; & \log_2 |A_{\text{cell}}| \notin N_0 \\ b^* + 1; & \log_2 |A_{\text{cell}}| \in N_0 \end{cases} \quad (4)$$

where  $N_0$  represents the set of natural numbers.

Based on the discussion above, Fig. 3 gives one of the assignment patterns for  $R = d$ . Nine addresses from 0 to 8 are allocated to virtual cells in a cell cluster, and only 4 bits are

needed correspondingly. The limited cell addresses are reused endlessly, and an infinite area can be covered in this way.

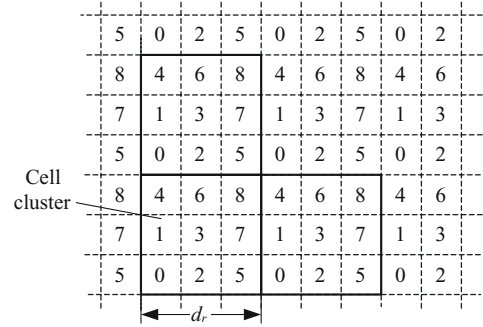


Fig. 3 Address assignment for cells

From Eqs. (3) and (4), it is known that the address size  $b$  is only a function of the average connectivity  $\lambda$ , which just depends on  $N$ ,  $S_{\text{area}}$  and  $R$ . So are the lower  $\lambda$  and the smaller  $b$ . As  $N$  and  $S_{\text{area}}$  are determined by the target of network design,  $R$  can be adjusted to reach the minimum value of  $b$ . Besides, considering  $R < d$  means that the communication range is lower than the average distance between neighbor nodes, which will lead to the partition of a network, so after excluding this meaningless case, following theorem can be got.

**Theorem 2** In VGSR, the address size  $b$  achieves its minimum when  $R = d$ .

### 3.3 Address mapping

In a cell cluster, the address increases from the low-left corner to the up-right corner regularly (as shown in Fig. 3), so exact mapping can be established from the coordinates  $(x, y)$  of sensor nodes to the cell address  $A_{\text{addr}}$  where the sensor located in easily

$$A_{\text{addr}} = \begin{cases} 2x_1 + y_1^2; & x_1 \leq y_1 \\ x_1^2 + 2y_1 + 1; & x_1 > y_1 \end{cases} \begin{cases} x_1 = [\text{int}(x/d)] \bmod a \\ y_1 = [\text{int}(y/d)] \bmod a \end{cases} \quad (5)$$

Here,  $a = d_r/d$  and  $\text{int}(x)$  is the largest integer lower than or equal to  $x$ .

### 3.4 Address collision resolving

In VGSR, most cells include only one node, but the possibility cannot be excluded that two or more nodes correspond to one cell in common. In order to enhance the robustness, VGSR takes the scheme which demands address declaration before using to resolve address collision efficiently. Moreover, to reduce overheads, data packets including addresses are taken as declaration in the form of piggybacking.

When a node detects the address that it will use has been declared by other nodes preemptively, it usually selects a new one randomly in the spare addresses and declares afresh. Besides, if a node receives a declaration for a spare address,

it should inform its neighbors “the address has been used” to avoid the address collision in two-hop range of the declarer. Nevertheless, in the extreme case where no spare address is available, the node shall turn to sleep. This measure makes sense as too many nodes have clustered in a local area excessively when this happens and it is unnecessary to activate more than necessary nodes so as to save energy. When some node exhausts, the sleeping one substitutes it and uses its address. In this way, excessive sensor nodes in a cell work successively, which benefits the extension of network lifetime.

## 4 Support to mobility of sensor nodes

The algorithm also suits mobile sensor networks. In this scenario, a mobile sensor node should check its variable position coordinates continually and judge whether it has entered a new virtual cell. If it still locates in the primary virtual cell, no actions should be taken. Otherwise, the sensor node listens to the channel for a period of time firstly and gets address use information of the new cell, then choose an address according to VGSR properly.

## 5 Simulation and analysis

In this section, a scenario is simulated with  $N$  nodes distributed uniformly over a square field with size of  $L \times L$  to evaluate the performance of VGSR. Every node sends its first data packet to declare MAC address at a random time at an interval of 10 s. The results are averaged over 500 simulations.

### 5.1 Typical scenario

In a typical scenario,  $N = 400$ ,  $L = 200$ , and  $R = 17.84$  m, such that  $d = 10$  m and  $\lambda = 10$ . Every node is pinpoint. In VGSR, the size of address is only 5 bits, which can provide 32 addresses, where 25 addresses are assigned for virtual cells, and the other 7 addresses are set to be spare addresses. Compared with the fixed size of 6 bits and the average size of 4.41 bits of encoded MAC address presented in Ref. [5], when  $\lambda = 10$  and 9 bits in globe unique address, the performance of VGSR improves greatly.

#### 5.1.1 Energy cost

The energy cost of VGSR is composed of two parts: address mapping cost and address collision resolving cost, which can be expressed as follows:

$$E_C = E_{\text{MappingC}} + E_{\text{CollisionC}} = E_{\text{operation}_M} T_M + E_{\text{operation}_C} T_C \quad (6)$$

where  $T_M$  and  $T_C$  denote the operating times of address mapping and collision resolving respectively, and  $E_{\text{operation}_x}$  represents the cost of instruction for corresponding operation.

In a typical scenario,  $T_M = 1$  and  $T_C = 18.92$ . Due to the low cost of processing [3] and the limited operating times, the energy cost of VGSR is fairly low.

#### 5.1.2 Energy saving

Compared with 9 bits needed by global unique MAC address for 400 nodes, the energy saved by VGSR, denoted by  $E_s$ , is equal to Eq. (7).  $T_F$  is the total number of data packets sent by a node,  $E_{\text{bit}}$  is the energy cost for transmitting one bit and the factor 2 represents the address of sender and receiver in a packet.

$$E_s = 2(9 - 5)T_F E_{\text{bit}} \quad (7)$$

### 5.2 Influences of the average connectivity

The average connectivity of a sensor network can be changed by adjusting the communication range  $R$  of nodes. Figure 4 compares the address size in case of different  $\lambda$ . Obviously, the address size of VGSR is always superior to that of global unique address. Based on the curve, the address size of VGSR is determined by the average connectivity. The larger  $\lambda$  is, the more addresses are needed by VGSR. It is worth noting that when  $R = d = 10$  m ( $\lambda = 3.14$ ), VGSR reaches its minimum size, which is marked by a circle in Fig. 4. It is the very optimal point that is described by Theorem 2.

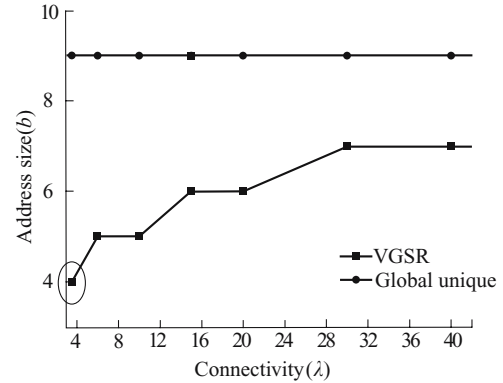


Fig. 4 Comparison of address size for different  $\lambda$

### 5.3 Scaling performance

Figure 5 shows the variation of address size with network scale. It is evident that the address size of VGSR is independent of  $N$ , and only determined by the average connectivity. Although  $N$  ranges from 50 to 5 000, the size of address remains a small value. Compared with the global unique address, VGSR scales perfectly with a network size.

## 6 Conclusion

Energy saving is a critical problem in the design of wireless sensor networks. Based on the analysis of MAC address

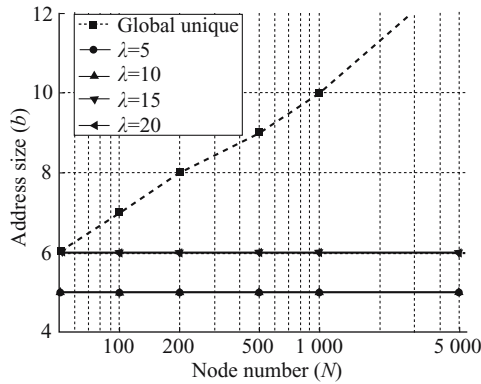


Fig. 5 Comparison of address size for different  $N$

reusing condition, a novel low-cost MAC address assignment algorithm VGSR is proposed in this paper. By reusing limited MAC addresses spatially, VGSR reduces the overhead of the MAC address of sensor nodes greatly and extend the lifetime of networks efficiently. Both theoretical and simulation results show that VGSR is not only of low energy cost, but also scales well with the network size, and can achieve the

optimal performance by adjusting the communication range of sensor nodes.

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