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DGR: dynamic gradient-based routing protocol for unbalanced and persistent data transmission in wireless sensor and actor networks*

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Abstract: This paper is concerned with the routing protocol design for large-scale wireless sensor and actor networks (WSANs). The actor-sensor-actor communication (ASAC) strategy is first proposed to guarantee the reliability of persistent actor-actor communication. To keep network connectivity and prolong network lifetime, we propose a dynamic gradient-based routing protocol (DGR) to balance the energy consumption of the network. With the different communication ranges of sensors and actors, the DGR protocol uses a data load expansion strategy to significantly prolong the network lifetime. The balance coefficient and the routing re-establishment threshold are also introduced to make the tradeoff between network lifetime and routing efficiency. Simulation results show the effectiveness of the proposed DGR protocol for unbalanced and persistent data transmission.

Key words: Wireless sensor and actor networks, Unbalanced and persistent data transmission, Gradient-based routing
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1 Introduction

Wireless sensor and actor networks (WSANs) are composed of a group of sensor nodes and actors connected by a wireless medium to perform distributed sensing and acting tasks (Akyildiz *et al.*, 2002; Akyildiz and Kasimoglu, 2004). For the cooperation of multiple actors to collaborate and complete a task, the actor-actor communication (AAC) (Melodia *et al.*, 2007; 2010) is required to exchange useful information among actors. However, the reliable direct transmission among actors is difficult to achieve in real ad-hoc networks deployed in a wide area. In this case, using the sensor network to support the communication among actors could be a reasonable solution (Selvaradjou *et al.*, 2010). When the actor cannot communicate with other actors through AAC, it could forward its data to the sensor network, and uses the sensor network to relay its data to the target actor. In this paper, we call this transmission pattern actor-sensor-actor communication (ASAC).

In ASAC, the communication is always carried out among a small group of actors, and the data load generated by actors could be much larger than the sensing data. Hence, the data transmission in ASAC is unbalanced and persistent. Since the communication among actors is assisted by sensor nodes with a limited resource, the balance of energy consumption of the whole sensor network is a crucial problem to be considered in the routing protocol for ASAC.

Many routing algorithms have been proposed to achieve high energy efficiency and low complexity for wireless sensor networks. Gradient-based routing is

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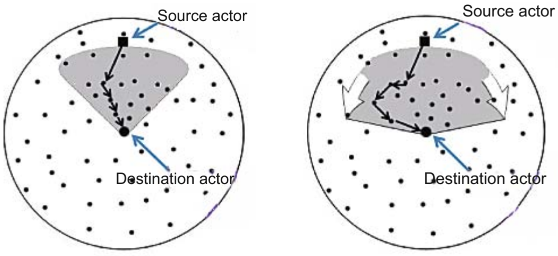
one of the reliable and efficient methods to transmit data with low overhead (Han *et al.*, 2004; Ye *et al.*, 2005; Huang *et al.*, 2009; Xu *et al.*, 2010). Here, gradient is the state of nodes representing the forwarding direction of data transmission towards the destination of data transmission, such as the sink. It could be set as the hop count, physical distance, etc. Thus, it could be used to establish the forwarding routing path.

One of the well-known gradient-routing protocols is the gradient broadcast (GRAB) protocol (Ye *et al.*, 2005). In the GRAB protocol, the gradient of the nodes is set to be the minimum energy consumption to transmit data packets from themselves to the sink. However, the gradient of GRAB needs to be periodically updated and flooded by the sink, which leads to high overhead. The state-free gradient-based forwarding (SGF) protocol (Huang *et al.*, 2009) is an advanced gradient-based routing protocol. It has a lower energy overhead cost because the gradient maintenance is driven by data transmission instead of periodic flooding. However, both methods are suitable for the networks where all the sensor nodes have the balance of data to transmit. They focus on the real-time applications and an energy-efficient way to connect the sensor nodes to the sink. Thus, these protocols cannot be directly applied to the unbalanced and persistent data transmission in ASAC. In ASAC, the source actor generates a large number of data packets to be transmitted to the destination actor. If the destination actor is out of the transmission range of this source actor, the source actor forwards these data to the sensor nodes around it, and then these sensor nodes transmit the data packets to the destination actor. This leads to regional energy consumption (the shadow region in Fig. 1a), and the sensor nodes in this region will be over-used because of transmitting persistent data packets. The over-used sensor nodes deplete much quicker than other nodes that are not used in this scenario. In fact, if the depleted nodes are in the unique routing path of the newly generated data packets, the data packet would fail to be transmitted to the destination actor. This will definitely cause unbalanced energy consumption over the network and shorten the network lifetime. On the other hand, the sensor nodes in the shadow region in Fig. 1a also consume energy in an unbalanced way. The sensor nodes in the most efficient path deplete faster. To the best of our knowledge, how to make full use of the limited network resource to transmit the unbalanced and persistent data is a problem not yet investigated.



(a) (b)

Fig. 1 Data transmission in actor-sensor-actor communication. (a) Unbalanced and persistent data transmission; (b) Data load expansion

To solve the problems stated above, we propose a dynamic gradient-based routing protocol (DGR) for the unbalanced and persistent data transmission in ASAC. In DGR, the gradient will be updated according to the energy consumption, and the routing algorithm is designed based on the updated gradient with the so-called expansion strategy (Fig. 1b), to involve more sensor nodes into the routing process.

2 Problem formulation and preliminaries

In this study, we design the DGR protocol to satisfy the goal of prolonging the network lifetime in the scenario of unbalanced and persistent data transmission. The network setup of the WSAN is as follows:

1. A large number of sensor nodes and several actors are randomly deployed in the WSAN. All sensor nodes have limited energy E_{MAX} and the actors are assumed to be of unlimited energy.

2. In ASAC, the data generated by one actor needs to be transmitted to another actor through the assistance of the sensor network. Without loss of generality, we assume that there is a destination actor located at the center of the network.

3. The data transmission generated by the source actor is unbalanced and persistent, which means that the communication among actors is regional, not evenly covering the whole network.

4. The maximum transmission ranges of actors and sensor nodes are represented by R_{A} and R_{S},

respectively. In practice, the transmission range of actors is always greater than that of sensor nodes. In this study, we assume that the actor can change the communication range by power control. The change rule will be introduced in Sections 3.2 and 3.3.

5. Sensor nodes run in two modes in the network layer. One is the idle mode in which the sensor nodes are running in low energy consumption with duty cycle. Sensor nodes in this mode periodically probe the transmission request from other nodes or actors. The other is the busy mode in which sensor nodes keep transmitting data until they finish the transmission and turn to the idle mode. All the sensor nodes are assumed initially in idle mode. As soon as a sensor node probes transmission request by the actor or other sensor nodes, it turns to busy mode.

6. It is necessary to guarantee that each sensor node can transmit data to each actor with at least one sensor node within the range of R_{S}. This can be guaranteed by sensor deployment (Younis and Akkaya, 2008).

3 Dynamic gradient routing protocol

The DGR protocol is developed based on the gradient routing protocols (Han *et al.*, 2004; Ye *et al.*, 2005; Huang *et al.*, 2009). In gradient routing protocols, each node has a gradient (usually the data transmission cost), representing the direction towards the sink. Data packets transmit on the direction of the descending gradient to guarantee that the data transmission is forwarding to the sink.

In most of the existing gradient-based routing protocols, the gradient field is always set at the very beginning, and will never be changed during the routing process, in order to minimize the overhead. However, since the ASAC process generates an unbalanced and persistent data transmission, the sensor nodes on the routing path will consume much more energy than the rest of the sensor nodes in the network. Thus, the existing methods cannot be applied directly. This will lead to unbalanced energy consumption over the network, which shortens the network lifetime. The DGR protocol builds up a dynamic gradient field to overcome the drawback. A sensor node in participation of routing will increase the gradient. Hence, the sensor nodes initially with the same gradient can become the next-hop relay nodes. The DGR protocol is likely to expand the data load to sensor nodes initially with the same gradient. This greatly increases the number of the candidates for the routing path.

Moreover, the dynamic gradient field is automatically updated according to the nodes' energy consumption with low overhead. The DGR protocol process includes three phases: the dynamic gradient setup phase, the routing path establishment phase, and the data transmission phase. In the dynamic gradient setup phase, each sensor node is set to the dynamic gradient. Then in the routing path establishment phase, a routing path is established between the source actor and destination actor based on the dynamic gradient of sensor nodes. In the data transmission phase, the data packets generated by the source actor are transmitted to the destination actor through the established routing path. The last two phases will be repeatedly driven by the routing path re-establishment strategy. The details of the phases and the routing path re-establishment strategy are described in detail as follows.

3.1 Dynamic gradient setup phase

In the DGR protocol, the dynamic gradient G is used to set the backoff timer of sensor nodes and actors in the routing path selection process. For a greater dynamic gradient G, the backoff timer of the sensor node is greater, and this sensor node has a lower probability of being selected as the next-hop relay node. The dynamic gradient G of the sensor nodes is defined as

$$G = k\alpha + s, \quad 0 < \alpha < 1, \tag{1}$$

where k is the cost gradient representing the minimum hop count by which the sensor node can transmit data to the destination actor, s is the energy gradient which represents the ratio of energy consumption of the sensor node, and α is the balance coefficient which is set to make tradeoff between network lifetime and routing efficiency. To guarantee that the data packets are forwarded, the dynamic gradients of the source actor and destination actor are set to be infinite and zero, respectively. The details of these parameters are described in the following subsections.

3.1.1 Cost gradient k

The cost gradient k is the hop count from the sensor nodes to the destination actor. It is a nonnegative integer used to guarantee the forwarding direction of the data transmission. We gain each node's cost gradient k by flooding an advertisement (ADV) message, which contains the sending node's k, namely k_{ADV}. The process of the cost gradient field establishment is given as follows:

Initially, the destination actor sets its cost gradient to be $k=0$ and broadcasts this ADV message with $k_{\mathrm{ADV}}=0$ in transmission range R_{S} in order to guarantee the network connectivity, in slot 0. The nodes receiving this ADV message set its k to $k_{\mathrm{ADV}}+1$. When slot i ends, slot $i+1$ begins and nodes with $k=i$ broadcast the ADV message with $k_{\mathrm{ADV}}=i$ in R_{S}. The process repeats until all the nodes receive the ADV message and set their own k. To avoid repeating flooding, nodes receive more than one ADV message, but they accept the first ADV message and ignore all the others.

3.1.2 Energy gradient s

The energy gradient s is designed to describe the utilization rate of sensor nodes. In this study, we define the energy gradient as the energy consumption rate, i.e.,

$$s=\frac{E_{\mathrm{MAX}}^{i}-E_{\mathrm{CUR}}^{i}}{E_{\mathrm{MAX}}^{i}}, \tag{2}$$

where E_{MAX}^{i} is the maximum energy (initial full energy) of node i, and E_{CUR}^{i} represents the current energy ratio of node i. The energy gradient s varies from 0 to 1, where 0 represents full energy and 1 represents a dead node.

3.1.3 Balance coefficient α

The balance coefficient α is used to achieve energy balance over the network. We expect to expand the data load forwarding to the sensor nodes with the same cost gradient k to achieve this goal. Balance coefficient α reduces the cost gradient k to a comparable effect with the energy gradient s on dynamic gradient G. In this way, the sensor nodes with the same cost gradient k may have lower dynamic gradient G. The balance coefficient α ranges from 0 to 1. For a smaller balance coefficient α, the cost gradient k has a weaker effect on dynamic gradient G. The data transmission among sensor nodes with the same cost gradient k prolongs the lifetime, but it reduces the routing efficiency. Hence, the balance coefficient α makes tradeoff between network lifetime and routing efficiency. In the performance evaluation section, we will make further analysis on α.

3.2 Routing path establishment phase

The routing path in DGR is set up based on the dynamic gradient of nodes. At first, we set a backoff timer for each node, namely t_{b}:

$$t_{\mathrm{b}}=T_{\text{max-delay}}\frac{G}{k_{\mathrm{MAX}}\cdot\alpha+1}, \tag{3}$$

where $T_{\text{max-delay}}$ is the maximum tolerable delay of the backoff timer, G is the node's dynamic gradient, and k_{MAX} is the maximum cost gradient in the WSAN. At the very beginning, $s=0$, and t_{b} is related only to the node's cost gradient k. All the sensor nodes are initially in idle mode. When a source actor generates data packets, it starts to establish a routing path to transmit data packets to the destination actor.

To establish a bidirectional path, the communication range of the source actor is set to be R_{S} for the routing path establishment phase.

In this process, two kinds of ADV message are used to send the request and agreement for a request to establish a communication path between two sensors or between a sensor and an actor: the transmission-request message (TR) and the transmission-agreement message (TA). Both the TR and TA messages contain the transmitter's ID and cost gradient k_{ADV}. The TR message contains two more pieces of information than the TA message, i.e., next-hop (NH) 'set/clear' and next-hop-id (NHID). At the very beginning, the source actor broadcasts a TR with NH 'clear' in the range of R_{A}. When an idle node receives this TR, it first turns to busy mode to check the NH message and k_{ADV}. If the NH is 'clear' and its k is not greater than k_{ADV}, it then holds the TR for time t_{b}. After t_{b}, it sends a TA to answer the request with transmission range R_{S}. When the source actor receives the first TA, it broadcasts another TR again. The TR is with the NH of 'set' and NHID of the set node's ID. After a node receives this TR and finds NH to be 'set', it checks whether the NHID is its ID. If not, the node drops the previous TR and goes back to idle mode. Otherwise, the sensor node becomes the next-hop relay node and uses the same method to find its next-hop relay node towards the destination actor with transmission range R_{S}. When the destination actor is set to be one node's next-hop, this path works and the data transmission phase starts. Thus, t_{b} is determined only by k. It routes through the least cost path initially. Algorithm 1 demonstrates the routing path establishment phase.

Algorithm 1 Routing path establishment

```
Set up random backoff timer $t_b$;
repeat
  if idle AND receive a TR message then
    turn to busy mode;
    if NH==clear AND $k <= k_{ADV}$ then
      hold the TR message;
      repeat
        if receive a new TR message then
          drop the previous TR message and turn to idle mode;
          return;
        end if
      until $t_b$ ends
      send TA message to answer TR message;
    else
      turn to idle mode;
    end if
  end if
  if busy AND receive the TR message then
    if NH==set AND NHI==ID then
      set to be the next-hop relay node;
      send the TR message to find next-hop relay;
    else
      drop the TR message and turn to idle mode;
    end if
  end if
  if receive the first response TA message then
    send the TR message to answer the TA message;
  end if
until the sink becomes a relay node
data transmission starts;
```

3.3 Data transmission phase

In this subsection, we use k_{source} to denote the cost gradient of the source actor. The maximum hop count r by which the source actor can transmit data by direct transmission in the routing path is defined as

$$r = \left\lfloor \frac{R_{\mathrm{A}}}{R_{\mathrm{S}}} \right\rfloor. \tag{4}$$

To achieve routing efficiency, the source actor uses its maximum power to transmit data directly to the sensor node with $k = k_{\text{source}} - r$ in its routing path. To achieve reliable data transmission, this sensor node sends ACK messages by r hops back to the source actor through the established routing path to answer the data packets transmission.

3.4 Routing path re-establishment strategy

In the routing path re-establishment strategy, we set the routing re-establishment threshold $\beta \in (0, 1)$. Each node in the routing path keeps checking whether the growth of its energy gradient s in this data transmitting phase has exceeded the routing re-establishment threshold β. If it does, the routing path re-establishment starts. The node sends an ADV message to the source actor, and the source actor will stop transmitting data packets and ask to re-establish the routing path. Nodes in the previous routing path switch to idle mode. In the re-establishment, the routing algorithm is the same as that discussed in Section 3.2. Compared with the initial routing path, some nodes have consumed energy and their dynamic gradients are raised. Hence, they have a high backoff timer and a longer response time to the transmission request. In this time, those candidate nodes with lower G become the members of the routing path. This demonstrates the dynamic routing strategy.

We can find that even though the data transmission is unbalanced and persistent, the sensor nodes in the routing path do not work for a long time. When the data transmission is detected to be persistent (i.e., some node over the threshold β), the candidate nodes will replace the over-used nodes to become the routing path members.

4 Performance evaluation

4.1 Simulation setting

We used OMNeT++ (www.omnetpp.org/) as the simulator to evaluate the performance of DGR. The network was set up as follows: 500 sensor nodes were randomly deployed in an area of 400 m×400 m, and the destination actor was set at the center of the area. The source data generated by the source actor was assumed to be infinite to present a typical situation for the unbalanced and persistent data transmission. The energy consumption model was borrowed from the model described in Heinzelman *et al.* (2000). The data transmission was scheduled by TDMA. The network parameters are summarized in Table 1.

Table 1 Network parameters

Parameter	Value
Maximum energy (J/node)	2
Transmission range of sensor, R_{S} (m)	70
Transmission range of actor, R_{A} (m)	140
Data packet size (byte)	512
Transmitter electronics, E_{elec} (nJ/bit)	50
Transmit amplifier, ϵ_{fs} (pJ/(bit $\cdot$ m^2))	10
Path loss exponent	2
Transmission rate (kb/s)	4

In the following, we will analyze the performance of DGR on network lifetime. In these simulations, we compared the performance of DGR with that of the gradient-based hop-count routing protocol (GHCR) (Han *et al.*, 2004), which also uses hop count to build a static gradient for forwarding data transmission. We will also analyze the impact of balance coefficient α and routing re-establishment threshold β on the performance of DGR.

4.2 Network lifetime

Network lifetime is the primary metric to evaluate the energy efficiency in WSANs. It is defined as the time until the data cannot be routed in any path to the destination actor (Kumar *et al.*, 2005). This definition describes the maximum duration of an unbalanced and persistent data transmission between the source actor and destination actor.

Fig. 2 shows the network lifetime based on DGR and GHCR protocols. To achieve multi-hop ASAC, the distance between the destination actor and the source actor was set in the range of $(140, 185)$ m. The balance coefficient α and re-establishment threshold β were set to be 0.1 and 0.2, respectively.

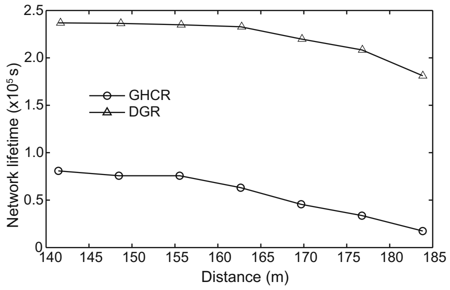


Fig. 2 Impact of the distance between the destination actor and source actor on network lifetime. The balance coefficient and routing re-establishment threshold were set to be 0.1 and 0.2, respectively

As shown in Fig. 2, DGR has over twice longer network lifetime than GHCR. It is because DGR could expand the data load to sensor nodes with the same cost gradient for persistent data transmission. These sensor nodes can establish the routing path with their next-hop relay nodes. Hence, DGR uses more sensor candidates to establish the routing path to balance the energy consumption.

Fig. 3 shows the number of active sensor nodes in the routing process during the persistent data transmission, where the source actor was set to be 160 m away from the destination actor. The number of active sensor nodes increased when the duration of data transmission varied from 20 000 to 60 000 s. This is because when the duration of the data transmission increases, DGR involves additional sensor nodes to share the unbalanced and persistent energy consumption. In contrast, in GHCR, the routing paths are all established in the most routing efficient way. Hence, the number of active sensor nodes for GHCR does not grow as much as that for DGR. This leads to an unbalanced data transmission and a shorter lifetime compared with DGR.

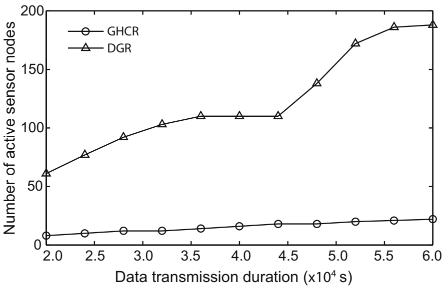


Fig. 3 Impact of data transmission duration on the number of active sensor nodes. The source actor was set to be 160 m away from the destination actor

4.3 Parameter determination

As mentioned above, balance coefficient α and routing re-establishment threshold β are used to balance the network lifetime and the routing efficiency in DGR. Figs. 4 and 5 show the effect of α and β on the network lifetime and energy consumption. The source actor was set to be 160 m away from the destination actor. In Fig. 5, the data transmission duration was set to be 160 000 s.

When α and β increased, the lifetime was shortened (Fig. 4). For a fixed data transmission duration, larger α and β led to less network energy consumption (Fig. 5), resulting in a greater routing efficiency. Figs. 4 and 5 show us how α and β affect the performance of DGR. When α increases, the cost gradient k

has a stronger effect on the dynamic gradient G. The sensor nodes with the same gradient are less likely to be chosen in the routing path establishment phase. Hence, the data transmission runs with greater routing efficiency while the network lifetime is shortened. In addition, when β increases, the data transmission process re-establishes the routing path in a lower frequency. In this way, the data transmission can have more time on the routing path with greater routing efficiency, which shortens the network lifetime. Hence, we can adjust these two parameters to achieve the tradeoff between network lifetime and routing efficiency of DGR.

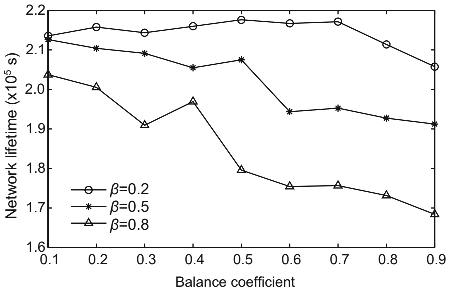


Fig. 4 Impact of balance coefficient α and routing re-establishment threshold β on network lifetime. The source actor was set to be 160 m away from the destination actor

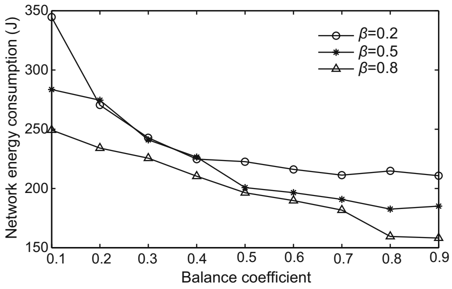


Fig. 5 Impact of balance coefficient α and routing re-establishment threshold β on network energy consumption. The source actor was set to be 160 m away from the destination actor. The data transmission duration was set to be 160 000 s

5 Conclusions

The dynamic gradient-based routing protocol (DGR) is proposed for unbalanced and persistent data transmission for ASAC in wireless sensor and actor networks. Considering the energy consumption rate as a part of the gradient, we designed the routing re-establishment strategy to balance the energy consumption distribution over the networks. This also makes more sensor nodes available for data transmission, and hence prolongs the network lifetime. Simulation results show that our DGR protocol can effectively prolong the network lifetime. Moreover, we achieve a tradeoff between network lifetime and energy efficiency by adjusting the balance coefficient and routing re-establishment threshold.

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