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SINK-INDEPENDENT MODEL IN WIRELESS SENSOR NETWORKS

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Abstract. Wireless sensor networks generally support users that send queries and receive data via the sinks. The user and the sinks are mostly connected to each other by infrastructure networks. The users, however, should receive the data from the sinks through multi-hop communications between disseminating sensor nodes if such users move into the sensor networks without infrastructure networks. To support mobile users, previous work has studied various user mobility models. Nevertheless, such approaches are not compatible with the existing routing algorithms, and it is difficult for the mobile users to gather data efficiently due to their mobility. To improve the shortcomings, we propose a view of mobility for wireless sensor networks and propose a model to support a user mobility that is independent of sinks.

Keywords: Agent, user, communication model, user mobility, sensor networks

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Mathematics Subject Classification 2000: 68M10 (Network design and communication)

1 INTRODUCTION

In wireless sensor networks, the user and the sinks are mostly connected to each other by infrastructure networks [1]. The users, however, should receive the data from the sinks through multi-hop communications between sensor nodes if such users move around the sensor networks without infrastructure networks [4].

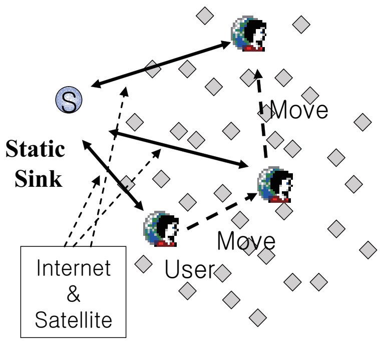

Fig. 1. Direct user-network communication model

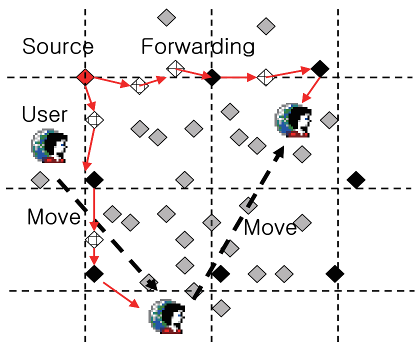

Fig. 2. GPS-based user-network communication model

To support mobile users, previous work has studied various user mobility models: the direct user-network communication model, the GPS-based user-network communication model, and the topology-control-based user-network communication model.

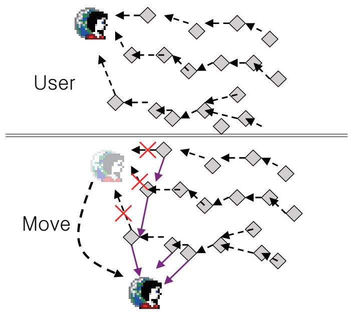

Fig. 3. Topology-control-based user -network communication model

Mobility Type	Compatibility with Existing Static Sink Routing Protocols	Feasibility	GPS receivers for sensor nodes	Control Overheads according to user mobility	Control Overheads to support multiple users	Help of infra-structure networks
D-COM	High	Low	Needless	Low	Low	Mandatory
G-COM	Low	Middle	Mandatory	Middle	Low	Needless
T-COM	Low	High	Needless	High	High	Needless
A-COM	High	High	Needless	Low	Low	Needless

Table 1. A taxonomy of mobility type

The direct user-network communication model (D-COM) is shown in Figure 1. It supports the mobility of a user on the assumption that the user communicates directly with sinks through infrastructure networks [1]. But, in applications such as rescues in a disaster area or maneuvers in a war zone, circumstances without infrastructure networks are more prevalent. Hence, the assumption that a user and a sink can communicate directly is not entirely accurate. The GPS-based user-network communication model (G-COM) is shown in Figure 2. G-COM is source-based topology [4, 5]. In G-COM, a sensor node (i.e. source) with a stimulus is going to make a GRID in a sensor field. Once a GRID is set up, mobile user floods its interests within a cell only where the user is located. When a sensor node closest to GRID points (henceforth called dissemination nodes) receives interests, it sends these interests to the source along a GRID path, and data from the source are forwarded to the user along the reverse path. The topology-control-based user-network communication model (T-COM) is shown in Figure 3. It also identifies a user with a sink. This model supports the mobility of the user by reflecting the movement of the user [7]. In T-COM, the user and sensor nodes proactively construct a tree that is rooted at the user. The user always maintains the tree and gathers data from sensor nodes.

Intuitively, G-COM and T-COM seem to be suitable for supporting user mobility. But, these models cannot use existing effective data collection algorithms [2, 3] between a sink and sensor nodes because of low protocol compatibility. Accordingly, such algorithms can hardly be exploited if users in sensor networks have mobility.

The other problem is that the cost of the overhead to reorganize the network topology and reconstruct dissemination paths from sensor nodes to the mobile user is expensive. In G-COM, all sensor nodes make the topology based on its own GPS receiver. The cost of GPS receivers is decreasing, but the overall cost is still high. In T-COM, similarly, user mobility causes topology reconstruction. If users move into a new location, then the root of trees must be changed, as seen in Figure 3. This leads to enormous overhead to sensor nodes.

This paper proposes a novel agent-based user-network communication model (A-COM). A-COM has the compatibility with existing static sink routing protocols. In addition, the users in A-COM do not make a topology and communicate only with agents. So, the users are free from topology control even if the sensors have no GPS receivers. Nevertheless, the movement of the user is supported by only sensor nodes.

2 MODEL ANALYSIS

In our model, the user appoints a sensor to act as an agent and forwards an interest to the agent. If there is one or more sink(s), the agent forwards interests to sensor networks via sink(s). The number of sinks, however, depends on the network policy. A network administrator might want to set a single or more sinks in the sensor field, or alternatively the sensor field may be hazardous as it cannot reach the field. Hence, we consider three scenarios according to the number of sinks.

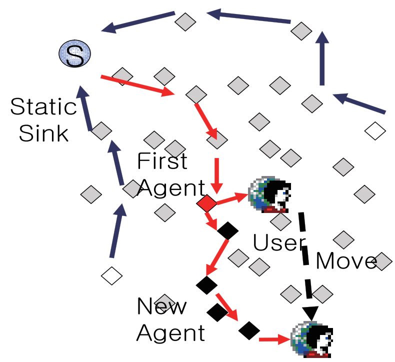

Fig. 4. Sensor fields with only one sink

2.1 Scenario 1: Sensor Fields with Only One Sink

If a sink is located in an arbitrary position in sensor fields, it floods a sink announcement message to announce itself inside the whole sensor field. As a result of the flooding announcement message, every sensor node knows the hop counts and next hop neighbor sensor node to the sink. While moving, if a user wants to collect data, the user selects the nearest node as a first agent, as shown in Figure 4. The user

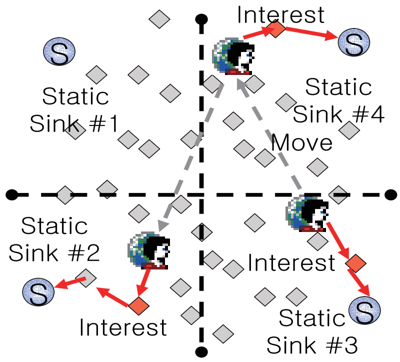

Fig. 5. Sensor fields with multiple sinks

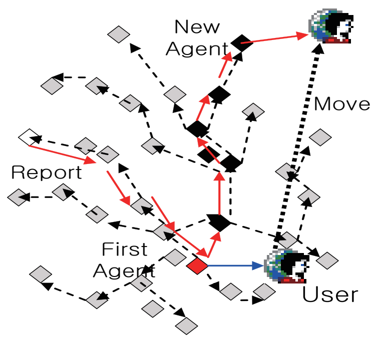

Fig. 6. Sensor fields with no sink

delivers an interest to the first agent and the first agent forwards the interest to the sink. If the sink receives the interest, existing routing algorithms for a static sink can be used to gather data (e.g., routing algorithms collecting data by periods or routing algorithms collecting a minority event). If all data are gathered by routing protocols, the sink aggregates all data and forwards an aggregated data to the first agent. A user may move to another place after sending an interest to the first agent. In this case, the user selects another agent that can communicate with the first agent. Also, the user makes a new connection between the newly selected agent and the original agent. (While moving, the user can make more agents and connections.) These agents and connections are used for forwarding the data from the sink.

2.2 Scenario 2: Sensor Fields with Multiple Sinks

Basically, the difference between Scenario 1 and Scenario 2 is only the number of sinks. As a result of sink announcement message dissemination, all sensor nodes know the nearest sink according to the hop counts. Accordingly, Interest dissemination of the user targets the nearest sink from the agent, as shown in Figure 5. If the targeted sink receives the interest, the interest is shared by multiple static sinks through the infrastructure network and each sink gathers data by routing protocols. (Various papers in relation to multiple static sinks indicate the connection between all sinks as an assumption [6, 8]. Therefore, in this paper, it is assumed that each sink can communicate with the other sinks via the infrastructure networks.) In this scenario, mobility support of the user and data propagation of the sink is still the same with Scenario 1. The user can receive the data from the nearest sink to its position. This saves energy, enhances the data delivery ratio, and reduces delay. In addition, users may not be able to recognize how many static sinks are in the sensor fields. This means that the proposed model is independent of the number of sinks.

2.3 Scenario 3: Sensor Fields with No Sink

In this case, users appoint the nearest sensor node as first agent, and the first agent disseminates the sink announcement message. As shown in Figure 6, users examine nearby sensor nodes whether there is a sink in the sensor field or not. If there is no sink, users appoint the nearest sensor node as first agent. Once a sensor node becomes the first agent, it acts as the sink of Scenario 1. Hence, other processes such as sink announcement message dissemination, interest dissemination of the user, mobility support of the user, and data propagation of the sink are the same as in Scenario 1. In this scenario, the first agents are appointed whenever users want to send their interests. Then, the first agents are reactively selected and perform all processes for user mobility. In the whole network, therefore, the sensor network can remain in an idle state. This is a positive effect because there is no control of messages and interests in the idle state sensor network.

3 OVERHEAD COMPARISON

In this section we analyze the efficiency and agility of A-COM. To compare each model fairly, we first assume several particulars and make note of some key facts.

Sensor deployment and user interests. Each model can be affected by a deployment of sensor nodes and network topology. To compare the models, we assume that each sensor node is uniformly deployed and every network topology needs to be maintained occasionally. We define a cycle C_m to maintain network topologies. That is to say, $C_m = c_1 T_i$ (c_1 is a constant number). The user can disseminate several kinds of interests and the kind of interests depends on network policy. So, we assume that q kinds of interests are in the sensor networks. In addition, the user can disseminate an interest at an interval of every T_i seconds. We define "*active node*" as a sensor node which generates sensing data for user interest. Although all sensor nodes receive user interest, only several active nodes generate sensing data due to constraints specified in user interest. We assume that there are p active nodes for each interest.

The delay to guarantee the receipt of all data. All sinks and agents suffer from a delay to gather data from all active nodes. We define the delay for receipt of all data to the sinks as D_g and assume that D_g is proportional to the number of sensor nodes along the straight-line path from the sinks to the furthest sensor node.

3.1 Energy Overhead

3.1.1 Comparison of D-COM and Scenarios 1 and 2 of A-COM

We consider a square sensor field of area A in which N sensor nodes are uniformly distributed so that on each side there are approximately $\sqrt{N}$ sensor nodes (see Figure 7). There is one stationary sink and k users in the sensor field. Users move at an average speed v and have a transceiver of r radio range in an outdoor area. All interests control messages and data packets have a size l.

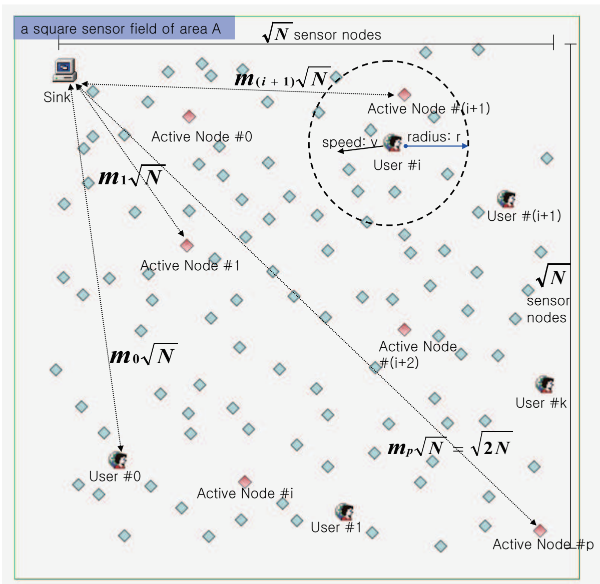

Fig. 7. A sensor field of area A

D-COM. In D-COM, the energy overhead to flood the sink announcement message is $N_f = N \cdot l$ because it is proportional to the number of sensor nodes. Once the sink announcement message is disseminated, all sensor nodes are divided into e leaf nodes and $\overline{e}$ non-leaf nodes. Then, the energy overhead to send the interest to the sink through the infrastructure is O_e. The sink floods the interest into the networks and the energy overhead to flood interest to the networks is $\overline{e}l$

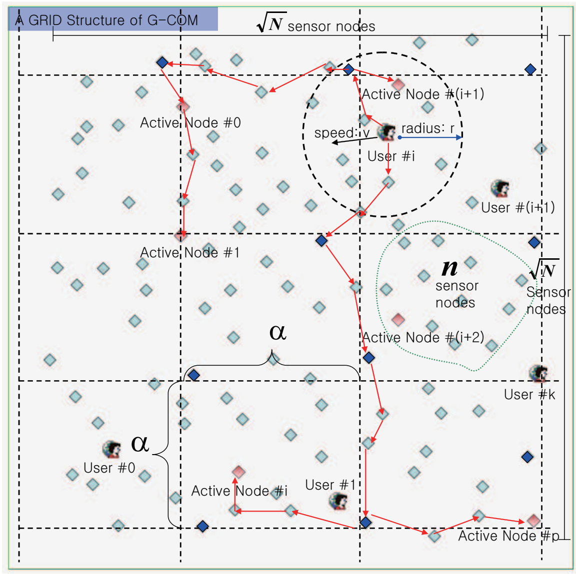

Fig. 8. A GRID structure of G-COM

because leaf nodes do not forward the interest. Once the interest is disseminated, p active nodes generate a data packet and forward it to the sink. The energy overhead to send data from the p active node to the sink is: $\sum_{i=0}^{p} m_i\sqrt{N}\cdot l$ where $m_i\sqrt{N}\cdot l$ is the number of sensor nodes along the straight-line path from the active nodes to the sink ($\forall i \in Z,\ if\ i \geq 0\ then\ 0 < m_i \leq \sqrt{2}$). If all data packets arrive at the sink, the user and the sink communicate directly, and the energy overhead to send the data packet to the sink is O_e. In addition, the sink refreshes the network topology by sending a sink announcement message in each cycle C_m because there can be a failure of the sensor node. Hence, the energy overhead to refresh network topology during $1 \cdot T_i$ is: $\frac{N_f}{C_m/T_i} = \frac{NlT_i}{C_m}$. Therefore, the energy overhead for k users to disseminate user interest and to gather data from sensor nodes during $1 \cdot Ti$ is $k\left(2O_e + \overline{e}l\ +\ \sum_{i=0}^{p} m_i l\sqrt{N}\right) + \frac{NlT_i}{C_m}$. By the way, the communication between the users and the sink does not require any energy overhead to the sensor nodes. In conclusion, the energy overhead of D-COM is $k\cdot\left(\overline{e}l\ +\sqrt{N}l\sum_{i=0}^{p} m_i\right) + \frac{NlT_i}{C_m}$.

Scenarios 1 and 2 of A-COM. In A-COM, a sink also initiates the sensor networks and forms a tree-type topology according to sink announcement message dissemination. If a user wants to send his/her interest to the sink and to gather data from the sensor networks, procedures of A-COM are similar to those of D-COM. A-COM and D-COM only differ in their method of sending interest to the sink and to receive data from the sink. In scenarios 1 and 2 of A-

COM, user k sends his/her interest to the sink and receives aggregated data from the sink through multi-hop communications between sensor nodes. Hence, the energy overhead to send an interest to the sink and to receive aggregated data from the sink is $km_{p+1}\sqrt{N}l + km_{p+2}\sqrt{N}l$ where $m_{p+1}\sqrt{N}$ and $m_{p+2}\sqrt{N}$ are the number of sensor nodes along the straight-line path from a user to the sink $(0 < m_{p+1}, m_{p+2} \leq \sqrt{2})$. Therefore, the energy overhead of scenarios 1 and 2 of A-COM is $k \cdot \left(\overline{e}l\ + \sqrt{N}l \cdot \sum_{i=0}^{p+2} m_i\right) + \frac{NlT_i}{C_m}$.

3.1.2 Comparison of G-COM, T-COM and Scenario 3 of A-COM

G-COM. In G-COM, the active node divides the sensor field into cells; each has an area α^2 (see Figure 8). There are $n = N\alpha^2/A$ sensor nodes in each cell and $\sqrt{n}$ sensor nodes on each side of a cell. The p active nodes first flood probe message, which is for confirming existence of other GRIDs made by other active nodes, where it is located.(if there is another GRID, the active node only registers itself to the GRID.) The GRID is constructed in proportion to q kinds of interests (see Figure 9).

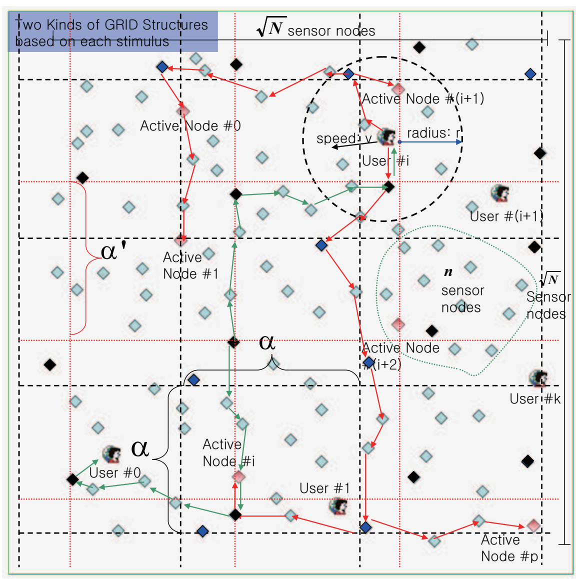

Fig. 9. Two kinds of GRID structures

The energy overhead to construct a GRID structure is: $q \cdot \left(pnl + 2\sqrt{N} \cdot \frac{\sqrt{A}}{\alpha} \cdot l\right)$ $= q \cdot \left(pnl + \frac{2Nl}{\sqrt{n}}\right)$ where pnl is the energy overhead for p active nodes to disseminate probe messages, $2 \cdot \frac{\sqrt{A}}{\alpha}$ is the number of straight-lines on the GRID.

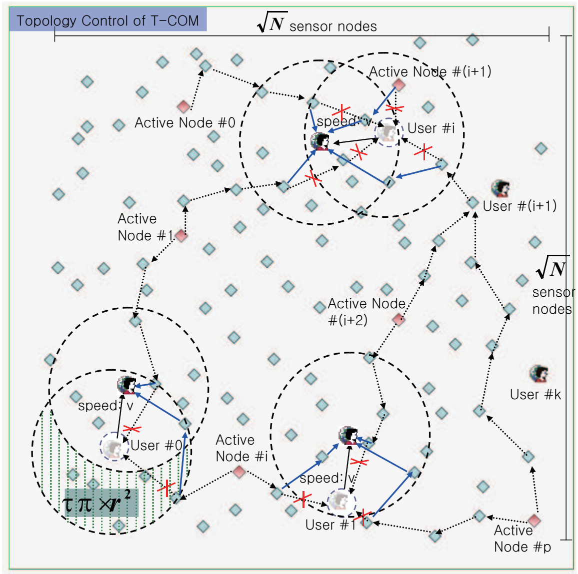

Fig. 10. Topology control of T-COM

Once a GRID is set up, k local mobile users flood interests within a cell only. When a dissemination node receives interests, it sends interests to the p active nodes along a GRID path and data from the p active nodes are forwarded to the users along the reverse path. The energy overhead for the interest to reach the active nodes and to forward data to the k users is: $k \cdot \left(nl + 2\sqrt{2}\sqrt{N}l \sum_{i=0}^{p} m_i \right)$ where nl is the local flooding overhead ($\forall i \in Z$, $if\ i \geq 0\ then\ 0 < m_i \leq \sqrt{2}$). In addition, the active node periodically refreshes the GRID structure by sending an active node announcement message in each GRID lifetime $G_m = c_2 T_i$ (c_2 is a constant number). The energy overhead to refresh network topology during $1T_i$ is: $\frac{q(pnl+2Nl)}{\sqrt{n} \cdot \frac{G_m}{T_i}} = \frac{q}{\sqrt{n}} \cdot \frac{(pn+2N)lT_i}{G_m}$ In conclusion, the network overhead of G-COM is: $k \cdot \left(nl + 2\sqrt{2}\sqrt{N}l \cdot \sum_{i=0}^{p} m_i \right) + \frac{q}{\sqrt{n}} \cdot \frac{(pn+2N)lT_i}{G_m}$.

T-COM. In T-COM, the topology is refreshed by sending a user announcement message in each cycle Cm. Hence, the energy overhead for k users to manage network topology during $1T_i$ is $kNlT_i/C_m$ where Nl is the energy overhead to flood the user announcement message. After a user moves at a speed v ($vT_i < 2r$), some sensor nodes within a radio range of user's previous location should change the path to the user, as seen in Figure 10. These sensor nodes send a path discovery message to find a path to the user and send a registration message to the sensor node which then sends a reply message of the path discovery message. Hence, the energy overhead for k users to manage the topology is $k \cdot (3N \cdot \tau\pi \cdot r^2/A)\, l$ where $\tau\pi \cdot r^2$ is an area which is out of radio range of the user due to user mobility$(0 \leq \tau < 1)$.

The energy overhead of T-COM to flood interest and to gather data is $kNl + k\sqrt{N}l \cdot \sum_{i=0}^{p} m_i$ $(\forall i \in Z,$ if $i \geq 0$ then $0 < m_i \leq \sqrt{2})$. In conclusion, the energy overhead of T-COM is $k \cdot \left(Nl + \frac{3N\cdot\tau\pi\cdot r^2}{A} \cdot l + \sqrt{N}l \cdot \sum_{i=0}^{p} m_i\right) + \frac{kNlT_i}{C_m}$.

Scenario 3 of A-COM. If k users want to flood an interest, each user appoints its agent and the agents flood the interest to the sensor networks. The data from active nodes are forwarded to the agents along the reverse path of the interest flooding. This reactive topology construction does not require topology management. Hence, the energy overhead for k agents to flood interests and to gather data is $k \cdot \left(Nl + \sqrt{N}l \cdot \sum_{i=0}^{p} m_i\right) + km_{p+1}\sqrt{N}l = k \cdot \left(Nl + \sqrt{N}l \cdot \sum_{i=0}^{p+1} m_i\right)$ where $km_{p+1}\sqrt{N}l$ is the energy overhead to forward data from agents to users.

3.1.3 Energy Overhead Analysis

To compare D-COM and scenarios 1 and 2 of A-COM, a sensor network consists of $N = 100$ sensor nodes; there are $\overline{e} = 40$ sensor nodes. Suppose $k = 2$, $E(m_i) = 0.5$, $p = 4$ and $C_m = 2T_i$, for a user to gather data packets:

$$(D - COM) : (A - COM) = 170l : 190l.$$

This means the energy overhead of A-COM has only a little difference from that of D-COM. To compare G-COM, T-COM and scenario 3 of A-COM, in addition, suppose $k = 2$, $E(m_i) = 0.5$, $p = 4$, $n = 9$, $\tau = 0.3$, $q = 4$, $r^2 = \frac{1}{30} \cdot A$, $G_m = 2T_i$ and $C_m = 2T_i$, for user to gather data packets:

$$(G - COM) : (T - COM) : (A - COM) = 287l : 359l : 250l.$$

This means that the energy overhead of A-COM is less than the energy overhead of G-COM and T-COM. In conclusion, A-COM can manage sensor fields efficiently as well as D-COM, and A-COM generates less overhead than G-COM and T-COM.

3.2 Delay Overhead

Comparison of D-COM and Scenarios 1 and 2 of A-COM. If the delay of communication by the infrastructure is zero, the delay overhead of D-COM is $D_g \approx 2\sqrt{2N} \cdot d$ where d is the delay for a sensor node to forward a packet.

In the case of scenarios 1 and 2 of A-COM, the delay for a user to send its interest to a sink and the delay for a sink to send aggregated data to a user are needed. Therefore, the delay overhead of A-COM is $D_g + 2 \cdot \sqrt{2N} \cdot d \approx 4\sqrt{2N} \cdot d$.

Comparison of G-COM, T-COM and Scenario 3 of A-COM. An interest and data in G-COM traverses a GRID and the average number of sensor nodes from a user to an active node is $2\sqrt{N}$. Therefore the delay overhead of G-COM is $4d\sqrt{N}$. In T-COM, the delay for an user to disseminate an interest and to gather data is equal to the delay of D-COM. Therefore the delay overhead of T-COM is $2d\sqrt{2N}$. However, the delay overhead of T-COM may be more than that of scenario 3 of A-COM, because T-COM generates many collisions of data packets due to user mobility. This effect of packet collision will be shown in Section 4. In scenario 3 of A-COM, the delay for an agent to disseminate an interest and to gather data is also D_g, and the average number of sensor nodes from a user to an agent is $\sqrt{2N}$. Therefore, the delay overhead of scenario 3 of A-COM is $3\sqrt{2N} \cdot d$.

4 PERFORMANCE EVALUATION

We compare three mobility types in Table 1 with the proposed model in Qualnet, a network simulator. The sensor network consists of 100 sensor nodes, which are randomly deployed in a 300 m × 300 m field. And the user follows a random waypoint model of 10 m/s speed and 10 second pause time. The user disseminates an interest at an interval of every 10 seconds.

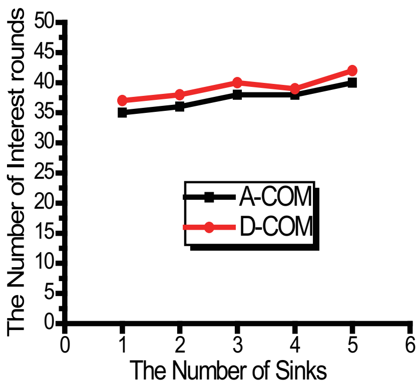

Fig. 11. Network lifetime for the number of sinks

Impact of the Number of Static Sinks. A difference between A-COM and the D-COM is how to communicate between a user and a sink. As shown in Figure 11, the network lifetime shows little difference between A-COM and D-COM. This means that A-COM can manage sensor fields as well as D-COM without infrastructure. In addition, the lifetime is increased according to the number of sinks. This is a side effect of multiple sinks. Users can use the shortest path to communicate with multiple sinks. Hence, the lifetime in A-COM is enhanced according to the number of sinks. The delay is also enhanced by this side effect of multiple sinks. A-COM basically has some delay due to multi-hop

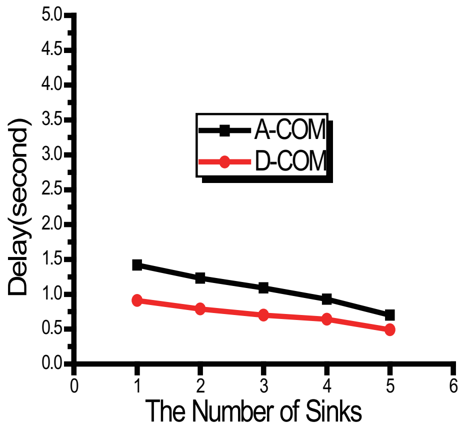

Fig. 12. Delay for the number of sinks

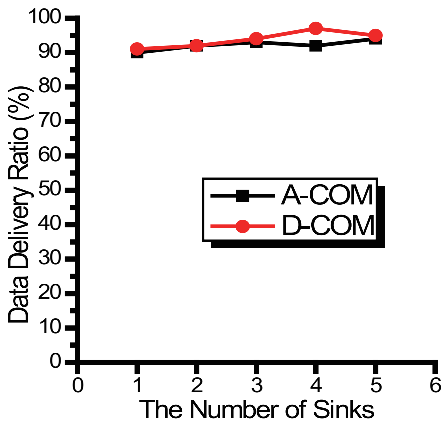

Fig. 13. Data delivery ratio for the number of sinks

communication between users and sinks. However, the delay is diminished according to the number of sinks, as shown in Figure 12. Nevertheless, the data delivery ratio of A-COM is comparable with D-COM, as shown in Figure 13. This also proves that the proposed model can manage sensor fields as well as D-COM without infrastructure.

Impact of the Number of Users. Generally, users generate its interest occasionally. Hence, sensors in Scenario 3 can save considerable energy. Alternatively, sensors in G-COM and T-COM maintain a topology continuously. As shown in Figure 14, the lifetime of T-COM is considerably low due to frequent topology change and that of G-COM is relatively low due to GRID maintenance. In Figure 15, G-COM has little delay due to proactive GRID topology by the

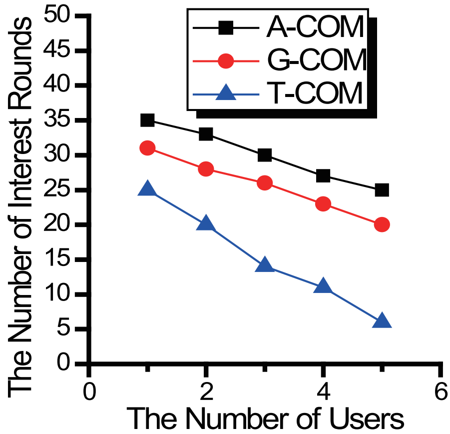

Fig. 14. Network lifetime for the number of users

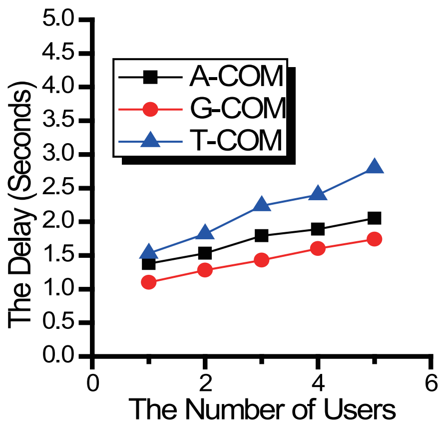

Fig. 15. Delay for the number of users

GPS receiver. T-COM proactively creates the topology, but frequent topology changes of T-COM delay data delivery considerably. The delay of Scenario 3, however, is only a little high due to the reactive first agent selection and topology construction. In the case of the data delivery ratio, A-COM and G-COM in Figure 16 are similar except for T-COM. The reason is that topology change messages disturb the data delivery ratio.

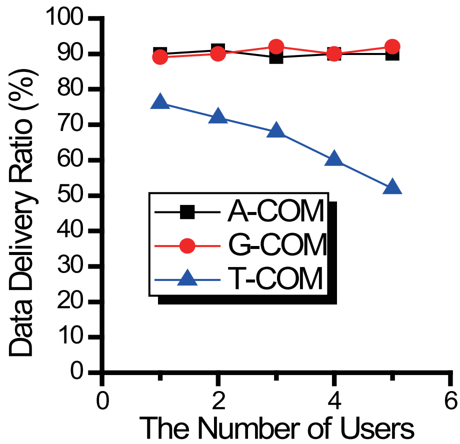

Fig. 16. Data delivery ratio for the number of users

5 CONCLUSION

In this paper, we propose a novel agent-based user-network communication model to support the mobility of users in wireless sensor networks. In the proposed network model, the user can receive data with a higher data delivery ratio and in a faster time without infrastructure.

We verified that the lifetime of sensor networks is prolonged because the reactive path construction decreases the energy consumption of sensor nodes. Also, we verified that performance of the data delivery ratio and the delay never falls; nevertheless, communication between the user and the network for guaranteeing movement of the user is supported by only sensor nodes without infrastructure networks.

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