# A BIOLOGICALLY-INSPIRED DATA-CENTRIC COMMUNICATION PROTOCOL FOR SENSOR NETWORKS *

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**Abstract** In this paper, we propose a new communication protocol for robust and scalable sensor networks. Our protocol, ARCP (Ant-based Rendezvous Communication Protocol) is based on the foraging behavior of ants. A sensor node that obtains sensor data emits data provision ants. On the other hand, a sensor node that needs sensor data emits data gathering ants. They wander around a sensor network while leaving pheromones.

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When an ant finds a trail of the other at a node, the node becomes a rendezvous point where data provision ants and data gathering ants meet and sensor data are passed from one to another. Since each ant moves on its own decisions in accordance with pheromones and no one ant has the dominant influence, ARCP is a fully distributed, robust, and scalable protocol.

**Keywords:** sensor network, data-centric, self-organizing, ant-based protocol

## 1. Introduction

In sensor networks, each application has unique characteristics different from others, including the area of region of deployment, a type of object to monitor, the number of sensor nodes, the number of nodes that provide sensor data, the number of nodes that need sensor data of others, and the frequency of needs for sensor data. In addition, those characteristics dynamically change in accordance with changes in conditions of surroundings, topology of a sensor network due to addition, removal, and movement of sensor nodes, and user's requirements. Therefore, a communication protocol for sensor networks must be adaptive to diverse and dynamically changing characteristics of applications. In addition, since sensor nodes are prone to failure, a communication protocol must be robust to failures of sensor nodes and faults in sensor nodes. Furthermore, to be scalable to the number of sensor nodes and the area of the region, a communication protocol must operate in a fully-distributed and self-organizing fashion.

Directed diffusion [1] is a data-centric communication protocol, which is called two-phase pull later by themselves. In sensor network applications, one specifies sensor data of interest not as "sensor data of sensor node x", but as "which part of the field goes beyond 40°C ?", "where are my friends?", or "when a fire is detected, let me know". This kind of communication paradigm is called *data-centric*. By directed diffusion, a sink can gather sensor data by only emitting messages called *interest*, without knowing who have sensor data. A node that requires sensor data first announces its need by diffusing interests by flooding and becomes a sink. Eventually interests reach sensor nodes that can provide requested sensor data and they become sources. Sensor data move from a source toward to the sink following paths that interests traversed. A path with the minimum delay is reinforced by the sink and sensor data are sent more frequently on the path. In [2], they proposed other two types of diffusion schemes, *i.e.*, one-phase pull and push. In the case of one-phase pull, the goodness of a path is determined by a source by assuming the symmetry of radio communications (but it does not usually hold). Push diffusion was intended for a type of application where there are many sinks, but there were few sources or many sources with the infrequent rate of data generation. Sources become active and advertise the presence of sensor data by disseminating exploratory data. On the other hand, sinks are passive and wait for sensor data. These diffusion protocols are considered robust to failure of nodes, faults in nodes, and loss of messages, since they adopted a flooding scheme to disseminate interests and exploratory data. However, as a consequence, it puts much load on a sensor network, consumes much energy of sensor nodes, and shorten the lifetime of a sensor network. Furthermore, they are not scalable to the number of sensor nodes.

In [2–3], they also proposed another approach that fell within a middle of push and pull diffusion, that is, rendezvous. In a rendezvous approach, interests and presence of data are sent to a pre-determined rendezvous point. If there is a match, a path is created. In [3], they compared the performance of four types of schemes in various scenarios and showed that a rendezvous-based approach could reduce the signaling overhead. In addition, they also showed that the performance of a rendezvous-based approach became much worse than the others when the location of a rendezvous point was wrongly determined. However, they did not show any perspective of locating the optimal rendezvous point. A rendezvous point must be located at the middle of the shortest path among sources and sinks, and thus, must be adjusted in accordance with changes in locations of sources and sinks and the frequency of communications.

In this paper, we propose a new data-centric communication protocol for a sensor network, taking inspiration from biological system, more specifically, the foraging behavior of ants as in [4–7]. We take a rendezvous-based approach since it can adapt to variety of applications and changes of application's requirements. In our ARCP (Ant-based Rendezvous Communication Protocol), ants are emitted from both of sources and sinks. Ants sent from sources are called *data provision ants*. Ants originating from sinks are called *data gathering ants*. They wander around a sensor network while leaving pheromones at sensor nodes. When an ant finds a trail, *i.e.*, pheromones, of the other type of ant, a rendezvous point is established at the node. The ant which establised or found an RP goes back to its originating node while leaving rendezvous pheromones at nodes it traverses. Other ants from sinks or sources can easily reach the rendezvous point by following rendezvous pheromones. Data provision ants put sensor data at a rendezvous point and data gathering ants take sensor data of interest from a rendezvous point. Since there is no centralized control and ants behave independently of others, there occasionally appear many rendezvous points. In addition, since rendezvous points are accidentally generated, they are not located at preferable positions among sources and sinks. To tackle the problem, we consider mechanisms for multiple rendezvous point to migrate to more preferable position and then merge together.

The rest of this paper is organized as follows. Section 1.2 describes our protocol ARCP. Section 1.3 shows some results of preliminary evaluations. Finally, section 1.4 summarizes this paper.

## 2. Ant-based Rendezvous Communication Protocol

In this section, we propose our ARCP. We assume that sensor nodes are deployed in a region to monitor in an uncontrolled and unorganized way. A sensor node can communicate with other sensor nodes in the range of radio signals. The number and locations of sources and sinks and the frequency of communications are not known in advance.

We consider that a sink expects to receive sensor data at the rate or frequency of $R_t$ [data/sec], which is determined by application's requirements. On the other hand, a source generates sensor data at the rate $R_s$ [data/sec]. For example, a sensor node which detects a certain event becomes a source and generates sensor data at $R_s$ during the event.

### 2.1 Outline of ARCP

In ARCP, both sinks and sources generate control messages, *i.e.*, ants, one by one. Ants emitted by sinks are called *data gathering ants* and those emitted by sources are called *data provision ants*. Each of ant is categorized into forward and backward ant depending on their direction of migration. An ant puts three types of pheromone at nodes it passes depending on its type. Forward data gathering ants leave data gathering pheromones which indicate the direction of sinks. Forward data provision ants leave data provision pheromones which indicate the direction of sources. Both of backward data gathering ants and backward data provision ants leave rendezvous pheromones which indicate the direction of rendezvous points (RP). All pheromones are defined by data-oriented attributes. Thus, for example, data gathering pheromones are the same among ants independently of their sinks as far as they look for sensor data of the same kind.

First, forward ants wander a sensor network by randomly choosing the next node as illustrated in Fig. 1 (a). When a forward ant moves to a node, it sets a pheromone value for the neighboring node from which it comes. When a forward ant discovers pheromones of the other type

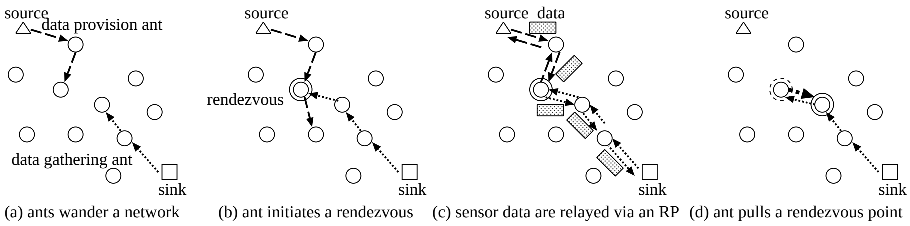


*Figure 1.* RP establishment and movement

of ants, it initiates a *rendezvous* and the node is marked as *Rendezvous Point (RP)* as illustrated in Fig. 1 (b).

A forward ant that initiates a rendezvous or finds an RP becomes a backward ant and it goes back to its originating node while leaving rendezvous pheromones on nodes it traverses. The form of a rendezvous pheromones is the same among backward data gathering ants and backward data provision ants for sensor data of the same attributes. By following rendezvous pheromones, forward ants can easily reach RP. Forward data provision ants leave sensor data at RP and go back to a source as backward data provision ants while leaving rendezvous pheromones. Forward data gathering ants go to an RP to take sensor data of interest from an RP and go back to a sink as backward data gathering ants while leaving rendezvous pheromone as illustrated in Fig. 1 (c). When a rendezvous point becomes unused, it is unmarked.

## 2.2 Generation of Ants

Forward data gathering ants are generated periodically at all sinks in a network. A TTL value is set for data gathering ants to avoid infinite wandering. A forward data gathering ant has a set of attributes that specify sensor data of interest. Since we consider a data-centric communication, there is no identifier of a sink. Forward data gathering ants that look for the same sensor data have the same form and leave the same data gathering pheromones. Therefore, a backward data gathering ant is attracted by data gathering pheromones that other ants from a different sink for the same sensor data left. Consequently, even if a sink emits forward data gathering ants at the desired reception rate $R_t$, an actual data reception rate becomes smaller.

In ARCP, each sink periodically regulates the generation rate $S_g$ of forward data gathering ants based on the expected data reception rate $R_t$ and the current data reception rate $R_c$. At the control instant, first, current data reception rate $R_c^+$ is updated from the previous reception rate $R_c$ as follows;

$$R_c \to \alpha R_c + (1-\alpha) R_p \ , \tag{1}$$

where parameter $\alpha$ $(0 < \alpha \leq 1)$ defines the weight of exponential moving average. $R_p$ corresponds to the minimum reception rate of sensor data during the last control period and derived as follows;

$$R_p = \min(r_s) \ , \tag{2}$$

where $r_s$ corresponds to the data reception rate from source $s$ during the last control period. $r_s$ can be obtained by analyzing identifiers of source in received sensor data. Then, the sending rate $S_g$ of forward data gathering ants in the next control period is derived as;

$$S_g \to S_g + \beta(R_t - R_c) \ , \tag{3}$$

where $\beta$ $(0 < \beta < 1)$ is a constant.

Forward data provision ants are generated each source at the rate $R_s$. A TTL value is also set for data provision ants. A forward data provision ant has sensor data, such as the temperature and the location of object.

## 2.3 Migration of Ants

**2.3.1 Forward Data Gathering Ant.** Forward data gathering ants aim to find a trail of data provision ants to establish a rendezvous point. Consider the case that a forward data gathering ant arrives node $i$. A forward data gathering ant chooses the next-hop node $n$ at random if there is no rendezvous pheromone on node $i$. If there is any rendezvous pheromones on node $i$, a forward data gathering ant chooses its next-hop node $n$ with the probability $P_r(n)$;

$$P_r(n) = \frac{T_r(i,n)}{\sum_{j \in N_i} T_r(i,j)} \ , \tag{4}$$

where $N_i$ is a set of neighbors of node $i$, and $T_r(i,n)$ corresponds to the rendezvous pheromone value to node $n$. Therefore, a path with more rendezvous pheromones attracts more forward data gathering ants.

Forward data gathering ants leave data gathering pheromones on the path to guide backward data gathering ant to a sink. By following a path with more data gathering pheromones, backward data gathering ants return to a sink while leaving rendezvous pheromones. Rendezvous pheromones further attract forward data gathering ants. Consequently, paths converge to only one and this spoils the robustness of the scheme. In addition, being attracted by much rendezvous pheromone, forward data gathering ants cannot find any other trails of data provision ants from other sources for the same sensor data. Therefore, we introduce the probability $p$, with which a forward data gathering ant takes a random walk even if there is any rendezvous pheromones at a node.

When an ant arrive a new node $i$, it updates the value of data gathering pheromone for node $j$ from which it came. The pheromone value $T_g(i,j)$ for node $j$ on node $i$ is given as $T_g(i,j) \rightarrow T_g(i,j) + \rho_g$, where $\rho_g$ is the amount that one ant leaves. At each time unit, the amount of data gathering pheromone decays as $T_g(j,i) \rightarrow T_g(j,i) - \sigma_g$, where $\sigma_g$ corresponds to the decay rate.

When a forward data gathering ant finds any data provision pheromones on a node it arrives and the node is not an RP, the node is marked as an RP. When a forward data gathering ant establishes or arrives an RP, it becomes a backward data gathering ant. When a forward data gathering ant reaches an RP without any data provision pheromones, it means that no data provision ant comes to the RP. Thus, the unused RP is unmarked. The following ants reach the pre-RP by being attracted rendezvous pheromones. From the pre-RP, since there are no pheromones except for data gathering pheromones on the node, they wander around to find a trail of data provision ants or another RP.

**2.3.2 Backward Data Gathering Ant.** A backward data gathering ant originates from an RP. It picks all sensor data cached at an RP, which match attributes of sensor data of interest. A backward data gathering ant goes back to a sink by following data gathering pheromones. In addition, it leaves rendezvous pheromones on all nodes that it traverses to guide forward data gathering ants to the RP. If there is no data gathering pheromone on node $i$, a backward data gathering ant chooses the next-hop node $n$ at random. If there is any data gathering pheromones on node $i$, a backward data gathering ant chooses its next-hop node $n$ with the probability $P_g(n)$;

$$P_g(n) = \frac{T_g(i,n)}{\sum_{j \in N_i} T_g(i,j)} \ . \tag{5}$$

On arriving a new node $i$, a backward data gathering ant updates the value of rendezvous pheromone for node $j$ from which it came. The pheromone value $T_r(i,j)$ for node $j$ on node $i$ is updated as $T_r(i,j) \rightarrow T_r(i,j) + \rho_r$, where $\rho_r$ is the amount that one ant leaves. At each time unit, the rendezvous pheromone decays as $T_r(j,i) \rightarrow T_r(j,i) - \sigma_r$, where $\sigma_r$ corresponds to the decay rate.

**2.3.3 Forward Data Provision Ant.** The behavior of forward data provision ants is about the same as forwarding data gathering ants, except that pheromones they leave are called data provision pheromones and they bring sensor data. If there is no pheromone on a node, the next-hop node is randomly chosen. If there is any rendezvous pheromones, it chooses the next-hop node with the probability given by Eq. (4). It also ignores rendezvous pheromones at probability $p$ to find trails of data gathering ants of other sinks. When it establishes or arrives an RP, it puts sensor data on the RP. An RP caches or updates the sensor data. If there is no data gathering pheromone on an RP, it is unmarked. Following data provision ants starts random-walk from the pre-RP node to find a trail of data gathering ants or another RP.

The amount $T_p(i,j)$ of data provision pheromones on node $i$ to node $j$ is updated as $T_p(i,j) \rightarrow T_p(i,j) + \rho_p$, where $\rho_p$ is the amount that one ant leaves. At each unit time, the data provision pheromone decays as $T_p(j,i) \rightarrow T_p(j,i) - \sigma_p$, where $\sigma_p$ indicates the decay rate.

**2.3.4 Backward Data Provision Ant.** The behavior of backward data provision ants is about the same as backward data gathering ants. A backward data provision ant chooses the next-hop node at random if there is not any data provision pheromones on a node. If there is any, the next-hop node $n$ is chosen in accordance with the amount of data provision pheromone on node $i$ as;

$$P_p(n) = \frac{T_p(i,n)}{\sum_{j \in N_i} T_p(i,j)} \ . \tag{6}$$

A backward data provision ant updates rendezvous pheromones at each node it traverses.

## 2.4 Rendezvous Point Position Control

As [3] suggested, the location of RPs affects the effectiveness of a rendezvous-based approach. We consider that an RP which is located at the center, from a viewpoint of hop count, TTL of ants, and emission rate of ants, of sources and sinks is desirable. If the emission rate of forward ants and their TTL are the same among sources and sinks, the node which minimizes the average length, *i.e.*, hops, of the shortest paths to all of sources and sinks is considered at the center. If there is a node with a higher emission rate, a rendezvous point should be closer to the node to reduce the load on a sensor network.

However, it is difficult to locate a rendezvous point at an appropriate position without any global information and centralized controls. Therefore, in our proposal, for an RP to be located at an appropriate node

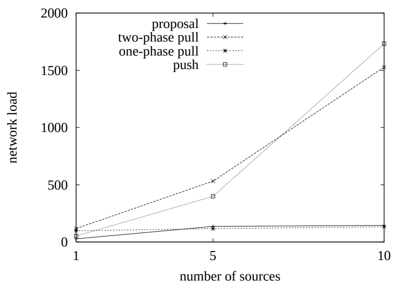


*Figure 2.* Network load (one sink)

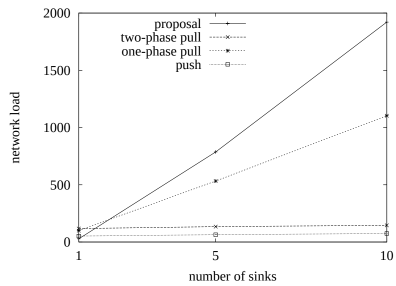


*Figure 3.* Network load (one source)

in a fully-distributed and self-organizing way, each ant pulls an RP in accordance with the distance from its origin to the RP as illustrated in Fig. 1 (d). When a forward ant arrives an RP, it moves the RP to the node from which it came with probability $P_m$ defined as;

$$P_m = \gamma \frac{h}{TTL} , \tag{7}$$

where $h$ corresponds to the number of hops that the ant experienced from its originating node to the RP and $\gamma$ is a constant ($0 < \gamma < 1$). $TTL$ is a initial TTL value of the ant set by its origin. When two or more RPs are moved to a node, they are merged together.

## 3. Simulation and Evaluation

In this section, we evaluate the performance of ARCP in terms of the adaptability, although we also conducted evaluations to verify the scalability and robustness of ARCP. We generated a network by randomly placing 60 nodes in a 50x50-m region and establishing links between nodes less than 12 m apart. The propagation delay of a link was identical and set at 1 msec. TTL value were identical among ants and set at 30. Sinks and sources were randomly chosen. As performance measures, we used the network load and the data reception rate. The network load corresponds to the number of control messages processed in a network per unit of time. The data reception rate corresponds to the number of sensor data received by a sink per unit of time and per source during a simulation experiment.

Due to space limitations, we only show results of evaluation of adaptability of our protocol to the number of sinks and sources. We varied both of the number of sinks and sources as one, five, and ten. In all cases, all sinks received sensor data at the expected rate. Figures 2 and

3 show that a diffusion protocol that led to the best performance changed in accordance with the number of sources and sinks. The reason that ARCP introduced much load as the number of sinks increased is that backward data gathering ants did not return to their originating sinks by being attracted by data gathering pheromones of other sinks. This is left as a future work.

## 4. Conclusion

In this paper, we propose a new communication protocol for robust and scalable sensor networks. Our protocol, ARCP, proposed taking an inspiration from biological system, is adaptive to application's requirements, scalable to the number of sensor nodes, and robust to failures of sensor nodes. Comparison with diffusion protocols, ARCP was verified to satisfy those characteristics required for a communication protocol for sensor networks. Some research issues still remain. We need a scheme to adaptively configure control parameters in accordance with several conditions including the topology of a sensor network and application's requirements.

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