Routing Research Based on Node Information and Node Mobility in Spare Sensor Networks

Xinxin DAI
School of Automation, Beijing Institute of Technology, Beijing, 100081, China
Tel.: 0086-10-68911231
E-mail: 1583483330@qq.com

Received: 30 December 2013 /Accepted: 28 February 2014 /Published: 31 March 2014

Abstract: For sparse sensor networks, through our quantitative analysis, a routing algorithm based on node information and node mobility, called NINMR, is proposed in this paper. By building a simple analytical model, we analyze the performance of NINMR by the number of mobile agent, probability distribution of meet time of sensor, probability distribution of interval meet time of sensor, the data success rate and the data delay. Simulation results show NINMR can increase data success rate, reduce required buffer capacities of mobile agent and decrease data delay. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Spare sensor networks, Routing algorithm, Node information, Node mobility, DataMULEs.

1. Introduction

Routing and forwarding are the most important thing for any networking technology. The existing self-organizing network routing protocols suppose that there is at least one unblocked path between the source and the destination node, so they are unavailable in the sparse sensor networks [1, 2]. In order to communicate between nodes in a disconnect networks, routers in the sparse sensor networks are working in “storage-carrying-forwarding” mode. In this mode, information will be cached on the current node and wait for a good opportunity to be forwarded with the node mobility when there is no node to jump to the destination [3]. It is the key point for an efficient sparse sensor network protocols design to decide when to jump and which node to jump to. Thus, the built and maintaining the operating of the routers degenerate into the choice of the node to jump to in the traditional networks, and we use “forwarding” instead of “routing” in this paper.

New mechanism will be used in sparse sensor network routers in order to adapt to the feature of the sparse sensor network [4]. The researchers of the DataMULEs system concluded as following [5]: 1) The storage demand of sensors is inversely proportional to the amount of mobile agents; 2) The storage demand of mobile agents is inversely proportional to the amount of mobile agents; 3) The storage demand of mobile agents is inversely proportional to the amount of access points; 4) the average meet time of sensors and mobile agents is inversely proportional to the amount of mobile agents; 5) The average meet time of access points and mobile agents is inversely proportional to the number of mobile agents.

In the DataMULEs system, the movements of mobile agents are totally random, and the meet time (MT) and the interval meet time (IMT) of mobile agents and sensors are both exponential distributions, so are the MT and IMT of mobile agents and access points. Reduction of MT and IMT
lead to reduction of data loss due to storage overflow. Because MT and IMT are exponential distributions, we have to increase the success rate by greatly increasing the amount of mobile agents or the storage ability of mobile agents and sensors. Reduction of IMT leads to a great reduction of transmission delay, and similarly, we need to greatly increase the amount of mobile agents and the amount of AP nodes to reduce transmission delay [5].

In this paper, by introducing the movable access point which is movable and of which path of motion is under control to change the structure of origin system to improve routing performance. The mechanism in this paper is called Node Information and Node Mobility based Routing (NINMR).

2. The Basic Idea

When the nodes are sparse or the topology changes are in strong randomness, a lot of routing waits for a better forwarding node passively. In this paper we use node mobility based routing in which some special nodes move on their own initiative to serve for other nodes’ communication.

In this paper, we treat the ubiquitous moving targets as the mobile agents, such as the animals in the habitat could become mobile agents; under the condition of traffic regulation, the transports could be the mobile agents. These mobile agents have wireless communication capabilities after installing short distance radio communication equipment. While they are moving, they can exchange data with the sensor or access points to finish the data transmission.

NINMR is based on DataMULEs system, the biggest defect of DataMULEs system is that the IMT of sensors and mobile agents and that of mobile agents and access points are too long. Packets is sent by sensors to mobile agents, and then sent by mobile agents to access points. So the data delay is related to the IMT of sensors and mobile agents and IMT of mobile agents and access points. And because of IMT being too long, packets stored on the sensor and mobile agents are too many which leads to more storage for sensor and mobile agents [6].

In the DataMULEs system, the IMT of mobile agents and a sensor is inversely proportional to the density of mobile agents that the more mobile agents are, the shorter the IMT of mobile agents and sensors is. The average of the delay time from sensors to mobile agents of packets generated during the IMT is also inversely proportional to the density of mobile agents. And the IMT of a mobile agent and access points is proportional to the area of the flat that the bigger the area of the flat is, the longer the MT is. The average of the delay time from mobile agents to access points of data stored on the mobile agents is proportional to the area of the flat. Thus, the IMT of the mobile agents and sensors is much less than that of mobile agents and access points.

To reduce the delay of the packets is mainly reduce the IMT of mobile agents and access points. There are two idea to reduce the IMT: one idea is that reduce the IMT by built of more access points which requires too much cost of built; the other one is that reduce IMT by the initiative movement which access points conduct to look for mobile agents.

In this paper we introduce an improvement plan according to the analysis above. We use the way that access points look for mobile agents to reduce MT of mobile agents and access points greatly by the initiative movement of mobile agents so that we can reduce the delay of data greatly. Access points choose their path by analysis on every node to reduce the MT of mobile agents and access points, the delay of packets and the requirement of sensors’ storage.

3. NINMR System Modeling

NINMR system is divided into 3 layers.

Top layer: access point (AP), including storage center, processing center and the WAN connection equipment of which the major functions are processing data, access to the WAN and so on, is the node which is under the control of the moving path.

Middle layer: the layer of mobile agents is formed by several passively moving nodes of which movement is random, and its function is to collect data from sensors and send the data to initiatively moving nodes.

Bottom layer: data collection layer, formed by a lot of fixed sensor with the ability of wireless communication, and its function is collecting data.

For a better study of the performance of NINMR, we limit and suppose parameters in NINMR as following:

1) Every node is in a limited and discrete two-dimensional space, and to simplify analysis, we suppose that the two-dimensional space is a discrete two-dimensional grid, in which all nodes are arranged as shown in the Fig. 1 which S stands for sensor, M stands for mobile agent, and AP stands for access points.

![Fig. 1. Areal model.](image-url)
2) Sensors and access points are only arranged in a small part of grids.
3) Internet is synchronized by a global clock, and every timing the following events occur: a sensor generates a group of data; a mobile agent moves from grid to grid.
4) The movement of a mobile agent is a kind of simple random movement that in every timing the probabilities it moves to the grid next to on each direction are the same; the movement of every mobile agent is independent of each other, and while some of them meet, they don’t exchange any data at all.
5) Mobile agents communicate with sensors and access points only when they are in the same grid.
6) We suppose that there is an enough bandwidth that all data stored in a sensor is able to be sent to a mobile agent during their meeting. Though oversampled, it is a practical hypothesis in a particular condition that only a little data needs to be sent.
7) We suppose that at each timing an access point is at the same grid with a mobile agent, which means that an access point visits one mobile agent at timing, and all the mobile agents are visited by turns.
8) There is a storage area for data storing for both a sensor and a mobile agent. While the storage area is not full, new data is able to be put into it, or the data will be discarded. Similarly, all data sent from sensors to mobile agents are only sent when the storage area isn’t full, or the data will be discarded. All storage area is empty at the beginning.

The model described above is simple, and doesn’t cover too many reality factors, such as the radio propagation, link fault and the bandwidth limit etc. Movement modeling is an important problem. Discrete random movement isn’t able to describe the movement of cars and people. But we can have a basic and visual aware of NINMR.

4. Theoretical Analysis

4.1. Basic Theories

The simplest condition is that there are only one mobile agent (\(N_{m}=1\)) and one access point. We suppose that the mobile agent and the sensor have unlimited storage ability, and the mobile agent conducts a simple symmetrical random movement, state space \(S\) is composed by grid on the flat which are able to be scanned to form a vector of which length is \(N(|S|=N)\). The simple model allow us to referent most of the conclusions of discrete-time and finite state Markov Chains. We estimate the average system performance by using the stationary distribution \(\pi = (\pi_i, i \in S)\) relying on the Markov Chains.

The probability with the state space \(S\) of the Markov Chains is:

\[
p_{i,j} = 1/4
\]

Because \(\sum_{i \in S} \pi_i = 1\) and all the probability is the same (such as \(\pi_i = \pi_j, \forall i, j \in S\)), we know that:

\[
\pi_i = 1/N
\]

Then we calculate the average IMT \(E[R_i]\) of the sensor \(i\) and the mobile agent. According to the theory of Markov we know that average time of a mobile agent’s arrival on the same is the reciprocal of stationary probability:

\[
E[R_i] = 1/\pi_i = N
\]

Because every timing a new data packet is created, the average IMT as well as the average usage of a sensor \(E[Z_i]\) (because \(SB = \infty\), the usage of buffer is equal to the summary of data created by sensors) when a mobile agent visits a sensor.

The results above provide some useful acknowledge, that is the system performance when number of grids changes. In formula (3), we can know it clearly that the IMT of a mobile agent moving to visit a sensor increases linearly with the number of grids increasing. This means two things: 1) Storage ability of a sensor need to change while the number of grids changes to avoid data loss; 2) Packets delay increases while the number of grids increases. These problems will lessen in the system with multi mobile agents.

4.2. The Influence of the Number of Mobile Agents on NINMR

We analyze the system with multi mobile agents. The percentage of data mules will not change while the number of grids increases, that is: \(N_m / N = \rho_m\). We calculate the average number of mobile agents which visit the sensor per unit time first, then we calculate the expectation of IMT of mobile agents and sensors.

Now, we think about one sensor and a particular data mule \(M_0\) of which the probably of meeting a sensor is:

\[
P(M_0) = 1 / N
\]

We define:

\[
Y_k = \begin{cases} 
0, & \text{The data mule does not intersect sensor at the moment } k \\
1, & \text{There are some data mule do not intersect sensor at the moment } k 
\end{cases}
\]

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So the probability of no mobile agent meets a sensor is:

\[ P\{Y_k = 0\} = (1 - \frac{1}{N})^{N_m} \Rightarrow \]

\[ P\{Y_k = 1\} = 1 - (1 - \frac{1}{N})^{N_m} \]

(6)

So the expectation of the number of mobile agents visiting sensors per unit time is that:

\[ mN \sum_{k=0}^{n-1} P\{Y_k = 1\} = 1 - (1 - \frac{1}{N})^{N_m} \]

\[ \Rightarrow 1 - e^{-\rho_m}, \text{ (when } N \text{ is large) (7)} \]

\[ \approx \rho_m, \text{ (when } \rho_m \text{ is small) (8)} \]

The IMT of mobile agents visiting a sensor is:

\[ E[R^{N_m}] = \frac{1}{1 - \left(1 - \frac{1}{N}\right)^{N_m}} \]

(9)

\[ \Rightarrow \frac{1}{1 - e^{-\rho_m}}, \text{ (when } N \text{ is large) (10)} \]

\[ \approx \frac{1}{\rho_m}, \text{ (when } \rho_m \text{ is small) (11)} \]

Proof: in order to calculate the IMT of sensor 1, we consider that the Markov Chains are composed by the Markov Chains of each mobile agent. So the new state space is:

\[ S' = S \times S \times \ldots \times S(N_{muals, \text{times}}) \]

In the developed state space S', we focus on state A represent one or many mobile agents meeting sensors. Because all states are probability-equaled, the stationary distribution of state A is calculated as follows:

\[ \pi(A) = \frac{|A|}{|S'| - |S' - A|} = \frac{N^N_m - (N-1)^N_m}{N^N_m} = 1 - \left(1 - \frac{1}{N}\right)^{N_m} \]

(12)

According to Kac’s formula, the expectation of a mobile agent meeting sensor i is:

\[ E[R^{N_m}] = \frac{1}{\pi(A)} = \frac{1}{1 - \left(1 - \frac{1}{N}\right)^{N_m}} \]

So we can calculate the expectation of usage of storage of a sensor with a big enough buffer is:

\[ E[SB] = E[R^{N_m}] \approx \frac{1}{\rho_m} \]

(13)

4.3. The IMT of Mobile Agents and Access Points

We suppose that the access points are fixed, and the IMT of mobile agents and access points is the reciprocal of the stationary probability:

\[ E[R_{ap}] = 1/\pi_i = N \]

(14)

By the equation (11), we can know that the mean of interval meet time of sensor and mobile agent is 1/\pi_i, that is N/N_m, so we can know that E[R^{N_m}] of E[R_{ap}] is N_m times, which is described as the following equation:

\[ E[R^{N_m}] = N_m E[R_{ap}] \]

(15)

Delay caused by the data from the production until the arrival of the mobile agent is positively associated with IMT between mobile agent and sensor, that is to say, the larger IMT, data to mobile agent longer, we can use the E[T_{s-m}] to represent the mean of the delay of the data reached the mobile agent; delay caused by the data from the mobile agent until the arrival of the connections is positively associated with IMT between mobile agent and connections, that is to say, the larger IMT, data to mobile agent longer, we can use the E[T_{m-ap}] to represent the mean of the delay caused by the data from the mobile agent to the connections. By the equation (15), we can know that as for multiple mobile agent system (when N_m is large), the delay E[T_{m-ap}] caused by data packet from mobile agent to connections much larger than the delay E[T_{s-m}] caused by the data packet from sensor to mobile agent, therefore, if we want to reduce the data...
packet delay, we can reduce the access time between data agent and connections.

As for the situation that the connections can move, the interval time, $R_{m}$, between mobile agent and connections is $N_{m}$, is much less than that situation in which the connections can not move, thus the data transmission delay will be reduced, and combining the equations above, we can know the mobile agent storage consumption expectation is:

$$E[MB] = \rho_s N_m E[R_{m}]$$

$$\approx \frac{N_m \rho_s}{\rho_m} \approx N \rho_s$$  \hspace{1cm} (16)

Similar to the inference before, we use the expectation of the interval meet time of the mobile agent as sensor storage consumption expectation when mobile agent accesses the sensor. Similar to the sensor memory usage, it is the mean of the data mule storage consumption only when the mobile agent and the connection point of intersection, because it is the average value of the data packets when mobile agent moves among the area that the mobile agent meet the connections continuously.

What’s more, we can conclude a conclusion, sensor storage requirement is only related with $\rho_m$, and the expectation of the sensor storage requirement is the reciprocal of the $\rho_m$, so if the $\rho_m$ dose not change, the sensor storage requirements will not change.

4.4. Probability Distribution of Meet Time of Sensor

The meet time of sensor i is defined as the first meet time of the mobile agent and sensor i, all the mobile agent will start with stationary distribution. We can find out the probability distribution of meet time of single mobile agent before we valued the situation of the multiple mobile agent system. Reference [7] indicated that the meet time of the single mobile agent which random move in the plane simply and symmetrically is $\Theta(N \log N)$. Besides, there is an analogy between the probability distribution of meet time of traversing Markov chain and the exponential distribution with the same average value [7]. So we can know:

$$P[H_i > t] = \exp\left(-\frac{t}{cN \log N}\right)$$  \hspace{1cm} (17)

where, $c=0.34$, $N \rightarrow \infty$($N \geq 25$). This result is the vision of the continuous time of discrete time for Markov chain, but this result is still right in the discrete time situation. The continuous time simplifies analysis, so all the probability distribution of meet time will be a continuous time chain. We can spread out the result of multiple mobile agent system.

All the mobile agents start with stationary distribution in the multiple mobile agent system, the meet time of sensor i is:

$$P[H_i^{N_2} > t_i] = \exp\left(-\frac{t}{0.34N \log(N)}\right)$$  \hspace{1cm} (18)

Prove: $H_i^{(k)}$ represent the time of a single mobile agent K hit sensor i, we can know:

$$H_i^{N_2} = \min_{k \in M} H_i^{(k)}$$  \hspace{1cm} (19)

Thus, we know:

$$P[H_i^{N_2} > t_i] = \{P[H_i^{N_2} > t_i]\}^{N_2}$$

$$= \exp\left(-\frac{t_i}{0.34N \log(N)}\right)$$  \hspace{1cm} (20)

4.5. Probability Distribution of Interval Meet Time of Sensor

To find out the interval meet time of sensor i, we consider firstly the situation in which there is only one mobile agent. In this situation, the interval meet time of sensor i is the same as the interval meet time of two times in a row of mobile agent and sensor i. For the smaller time slot and the limited size of mesh, this only provides a loosen upper bound for probability distribution.

To obtain the better characteristics, we can us the recursive equation to calculate $P[R_i = t]$ (probability distribution of interval meet time of single mobile agent). We can set the initial position of the mobile agent as the origin of the mesh. Define $L_{i,j}(t)$: the initial position is i, the end position is j, the length is t, the number of routs without passing through the origin. We can use $N(k)$ to represent the neighbor nodes of the node K. The following characteristic is available for all the nods i:

$$P[R_i = t] = L_{i,j}(t) / 4^t$$  \hspace{1cm} (21)

In the equation above, $L_{i,j}(t)$ represent the number of the effective paths to return the origin.
within t steps. \(4^t\) represents the number of paths of which the length are probably t steps. We can use the following recursive equation to calculate \(L_{0,0}(t)\):

\[
L_{i,j}(t) = \sum_{i \in N(i), j \neq 0} L_{i,j}(t-1), t > 1
\]

\[
L_{i,j}(1) = \begin{cases} 1, & \text{if } j \in N(i) \\ 0, & \text{else} \end{cases}
\]

The interval time of sensor i is:

\[
P[R_i^{N_s} > t] = P[R_i^{N_s-1} > t] \cdot P[R_i > t]
\]

Prove: to find out the probability distribution of interval meet time of sensor i, we only consider the situation in which a single mobile agent meet with sensor and ignore the situation in which mobile agents meet with sensor at the same time, because in the system which have less mobile agents, that situation is almost impossible, and the distribution of mobile agents left are stationary. So:

\[
R_i^{N_s} = \min(R_i, H_i^{N_s-1})
\]

4.6. Data Success Rate

There are some parts of data success rate above. The data success rate can be defined as the ratio of the average value of data packets which have been sent within t and the number of data packets, the data success rate as the following when the t tends to infinity:

\[
S = \sum_{k=0}^{\infty} \frac{E[\min(\rho_i, \min(R_i^{N_s}, SB), MB)]}{N_s N_s}
\]

Prove: we can obtain the data success rate according to the theory of the renewal reward [8]. A cycle is defined as a traversal which caused by the mobile agent traverse from the starting point and returns this point, so Nm is the length of a cycle. Sensor produce the data at the rate of the data packet per unit time, thus the average data that the system product per unit time is Ns, so we know that the data success rate is:

\[
S = \frac{E[\sum_{k=0}^{\infty} M^{(k)}]}{N_s N_s},
\]

where \(M^{(k)}\) is the data that the data mule obtain within Rap=\(\min\left((\rho_i^{N_s} \sum_{j=1}^{\infty} Y_i^{(k)}, MB)\right).\) The buffer capacity of the data mule limited the number of the data that the data mule can carry, so we use the min value. Now \(Y_i^{(k)}\) represent the number of the data that the sensor carried when K access the sensor at t.

We know from the following equation:

\[
Y_i^{(k)} = \min(Z_i, SB)
\]

Similar to the steps above, the upper bound of the sensor storage is the total number which sensor can carry, so we just use the min value. What’s more, \(Z_i\) is the total number of data which is produced by sensor but not be taken away, so it has the same distribution with the interval meet time of sensor.

5. Simulation Scheme and the Analysis of the Result

5.1. Design of the Simulation Scheme

We use the QualNet into our simulation experiment in this article. We put a connection on the center of the plane which is 1000 m * 1000 m and we also put 50 sensors random on it. The sensor produce the data packets at the rate of the data packet per second, the number of the mobile agents is 10 and it move random at the rate of 1 m/s and it send a node information packet per 1 s when it move. And mobile agent and connections add the information into the list of node information after accepting the node information. Mobile agent packet the information into the node information packet from the list while the connections set path according to the node information. We value the advantages of routing algorithm NINMR according to compare NINMR routing algorithm and success rate, storage consumption and data packet delay of DataMULEs system.

5.2. Analysis of the Result

1) Data success rate.

Simulation time is 50 minutes, the number of the data which is produced by the two systems is both 150,000. We defined the data success rate as the ratio of the number of the data packets which can arrive the target node within 50 munities and the number of the data packets which had produced within this time. The number of the data packets which were accepted successfully by NINMR routing algorithm is 91232, and the number of the data packets which were accepted by DataMULEs system is 25424, so the data success rate of the two systems is 60.8 % and 16.9 %.

2) Sensor and mobile agent storage consumption requirements.

The number of the data packets that were stored in the sensor NINMR is 35564 and the number of the data packets that stored in sensor DataMULEs is 34780 when the simulation is finished. The rate of the data packets that were stored in NINMR sensor and generation data packets is 23.7 % and the rate of the data packets that were stored in DataMULEs...
sensor and generation data packets is 23.1 %, because in the two systems, the average value of the time which caused by mobile agents which access the sensors is equal and the storage requirements of the sensor is equal too.

The number of the data packets that were stored in the mobile agent NINMR is 23204 and the number of the data packets that stored in mobile agent DataMULEs is 89796 when the simulation is finished. The rate of the data packets that were stored in mobile agent NINMR and generation data packets is 15.5 % and the rate of the data packets that were stored in mobile agent DataMULEs and generation data packets is 59.8 %, because in the two systems, the interval meet time which caused by mobile agent which access connections is totally different, interval time of which caused by mobile agent NINMR which access connections is much less than that in DataMULEs system, so the storage requirements of mobile agent NINMR is much less than that in DataMULEs system.

3) Data packet delay.

The difference between moment in which the data packet arrive the target node and the moment in which the data packets are produced is delay of the data packet arriving and the average point to point delay of data is 76.1 s, and the average point to point delay of data packet is 672.2 s. The delay of data packet in NINMR is much less than that in DataMULEs system, because the interval meet time of the two mobile agent which access connects is different, the interval time of the mobile agent NINMR which access connections is much less than that in DataMULEs system, so the delay of data in NINMR is much less than that in DataMULEs.

6. Conclusions

We can know the design idea of NINMR: when the nodes of the net are sparse or topology changes random, the routing algorithm based on redundancy or efficiency is waiting for the better routing nodes which leads to reducing the efficiency of transportation. In the routing algorithm based on nodes which move forwardly, some special nodes move forwardly to offer the communication service for other normal nodes so that they can increase efficiency of transportation. By building simple model, we can analysis the performance of the system through the aspects of effect of mobile agent on system performance, probability distribution of meet time of sensor, probability distribution of interval meet time of sensor and data success rate. We prove that routing algorithm have some advantages in the aspects of data success rate, mobile agent storage requirements and delay of data.

Acknowledgements

The research work was supported by National Natural Science Foundation of China under Grant No. 61101214.

References


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