This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2009 proceedings.

Message-by-Message Route Modification in Wireless Multihop Transmission for shorter Delay

Hiroaki Higaki
Department of Robotics and Mechatronics
Tokyo Denki University
Hatoyama Ishizaka, Hiki, Saitama, Japan +81-49-296-2911
Email: hig@higlab.net

***Abstract*—In a mobile ad-hoc network, network topology changes dynamically due to mobility of computers, battery consumption and failure of mobile computers. Until now, many adhoc routing protocol tolerating such changes of network topology have been proposed. Here, all data messages are forwarded by all mobile computers included in a message transmission route detected by an ad-hoc routing protocol. No intermediate mobile computers are added and removed other than in route repair and switching. This paper proposes a dynamic modification of a message transmission route for achieving shorter end-to-end transmission delay with less control messages in an adhoc network. Here, data messages are retransmitted not by a previous hop mobile computer but by another mobile computer which receives them correctly and is the nearest to a next hop mobile computer. This paper shows a routing protocol and a data message transmission protocol for the dynamic route modification according to the surrogate of retransmission. Performance evaluation is simulation shows that own proposal method achieves reduction of numbers of retransmission i.e., shorter end-to-end transmission delay, especially in a dense adhoc network.**

I. Introduction

Due to recent advanced computer and network technologies, mobile networks consisting of multiple mobile computers with wireless communication devices have been widely available. For achieving higher connectivity in spite of limited transmission power of wireless signal, wireless multihop transmission is applied for data message transmission from a source mobile computer to a destination one. A wireless multihop transmission route $R = \| M_0 \dots M_n \rangle\rangle$ from a source mobile computer $M_s (= M_0)$ to a destination one $M_d (= M_n)$, which is detected by an adhoc routing protocols such as DSR[5], AODV[10], TORA[8], DSDV[9], OLSR[6], FACE[11] and so on, is a sequence of intermediate mobile computers. M_0 transmits data messages to its next hop mobile computer M_1 on R. On receipt of a data message from a previous hop mobile computer M_{i-1} on R, each intermediate mobile computer $M_i (0 < i < n)$ on R forwards it to a next hop mobile computer M_{i+1}. Multihop transmission of a data message completes when M_n receives it from a previous hop mobile computer M_{n-1}. Therefore, in the conventional wireless multihop transmission, all data messages are transmitted along a wireless multihop transmission route detected by an ad-hoc routing protocol.

For data message transmission through each wireless link in wireless multihop transmission, a wireless LAN protocol such as IEEE802.11[1] and Bluetooth[2] is applied. Here, acknowledgement control messages for reception of data messages are introduced in hop-by-hop manner and data messages are retransmitted in case of no receipt of acknowledgement control message before timer expiration. Since successful transmission ratio through a wireless link is sometimes unstable due to change of distance between two successive intermediate mobile computers M_i and M_{i+1} by mobility and change of S/N ratio by transmission of wireless signals transmitted by other mobile computers and noise in an environment. Thus, a number of re-transmissions of a data message in a wireless link sometimes increases, end-to-end transmission delay gets longer and it may get temporarily difficult to transmit data messages along a wireless multihop transmission route detected by an ad-hoc routing protocol. In our proposal in this paper, in order to reduce a number of re-transmission of a data message and to achieve shorter end-to-end transmission delay, another neighbor mobile computer M of a next hop intermediate one M_{i+1} which is nearer to M_{i+1} than a current hop one M_i takes place of M_i and re-transmits the data message to M_{i+1}. Moreover, if M is in a wireless signal transmission range of a next hop mobile computer M_{i+2} of M_{i+1} on R, i.e. M is a neighbor one of M_{i+2}, it is possible for M not to re-transmit a data message to M_{i+1} but to transmit it to M_{i+2}, i.e. M_{i+1} is skipped.

As mentioned above, by dynamic addition (surrogate retransmission) and removement (skip of next hop) of intermediate mobile computers in a wireless multihop transmission route detected by an ad-hoc routing protocol, a number of re-transmission is reduced, end-to-end transmission delay gets shorter and a number of control messages are reduced. In this paper, we design a dynamic route modification protocol based on surrogate re-transmission by a nearer mobile computer to next hop one in each hop. In addition, a modified AODV routing protocol for the dynamic route modification is also designed. Though AODV-based protocols are described in this paper, it is possible for the proposed method to be applied to other ad-hoc routing protocols based on flooding of copies of a route request ($Rreq$) message and return of a route reply ($Rrep$) message.

978-1-4244-2948-6/09/$25.00 ©2009 IEEE

II. Surrogate Re-transmission

In a wireless LAN protocol such as IEEE802.11 and Bluetooth, if a data message from a transmitter mobile computer M_t is correctly received by a receiver one M_r, M_r sends back an acknowledgement control message Ack to M_t. Hence, in a wireless multihop transmission with a wireless LAN protocol, acknowledgement messages are transmitted in each hop in a wireless multihop transmission route, i.e. hop-by-hop acknowledgement is applied. If M_r does not receive a data message correctly, M_r does not send back an Ack control message to M_t. In this case, since M_t does not receive an Ack control message before timer expiration, M_t re-transmits the data message to M_r.

Under an assumption that wireless signal is transmitted through an omni antenna in each mobile computer, receipt power of the wireless signal is in inverse proportion to hth power ($2 \leq h \leq 4$) of distance d between M_t and M_r.

$$P_r = P_t(\frac{\lambda}{4\pi d})^h g_t g_r \quad (1)$$

Here, P_t, P_r, λ and d are transmission power, receipt power, wavelength and distance between M_t and M_r, respectively. In addition, g_t and g_r are transmission gain and receipt gain (constants), respectively. There may be many kinds of electromagnetic noise around a receiver mobile computer which prevents reception of wireless signals for data messages. Wireless signals transmitted by other mobile computers destined to other ones than M_r are also noise for M_r. In such an environment, probability P_s of successful transmission of a data message monotonically decreases to S/N ratio, i.e. to d as shown in this formula:

$$P_s = f(P_n/P_r) = f(P_n/P_t(\frac{\lambda}{4\pi d})^h g_t g_r) \quad (2)$$

As in Figure 1, a wireless signal transmitted from an intermediate mobile computer M_i on a wireless multihop transmission route R is not only received by a next hop one M_{i+1} but also overheard by all neighbor mobile computers of M_i in a wireless signal transmission range. In case that M_{i+1} does not receive a data message carried by this wireless signal correctly, the same wireless signal is re-transmitted by M_i after timer expiration in a conventional wireless LAN protocol. However, if another neighbor mobile computer M' of M_i and M_{i+1} nearer to M_{i+1} than M_i receives it correctly, higher probability of successful transmission is achieved by re-transmission not from M_i but from M'.

In order to realize this surrogate re-transmission, a neighbor mobile computer M of M_i should detect whether M is nearer to M_{i+1} than M_i or not. Moreover, if multiple neighbor mobile computers nearer to M_{i+1} than M_i receive a data message, it is required that the nearest one re-transmits the data message for achieving higher probability of successful transmission. Hence, a method for detecting the nearest mobile computer to M_{i+1} among ones receive a data message from M_i correctly is needed.

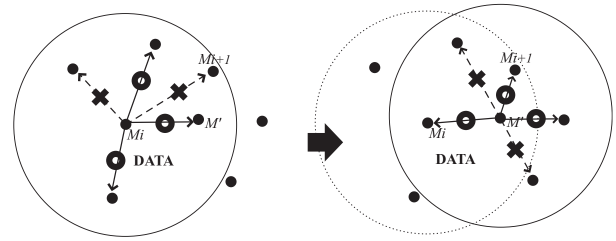

Fig. 1. Surrogate Re-transmission.

If a location acquisition device such as a GPS module is introduced in each mobile computer, by informing M of location information of M_{i+1}, M calculates $|MM_{i+1}|$. It is possible to implement this method by piggybacking location information of a mobile computer to route request $Rreq$ and/or route reply $Rrep$ control messages. Since M is in wireless signal transmission range of both M_i and M_{i+1}, M calculates both MM_{i+1} and M_iM_{i+1} by receiving an $Rreq$ message from M_i and an $Rrep$ message from M_{i+1} carrying location information. This method is combined to location-based ad-hoc routing protocols such as GEDIR[3], COMPASS[12], FACE, GFG[4] and GPSR[7]. On the other hand, if a location acquisition device is not introduced to mobile computers, a receiver mobile computer M_r estimates distance $|M_tM_r|$ from a transmitter mobile computer M_t by receipt power of an $Rreq$ or $Rrep$ control message from M_t according to formula (2). This method is combined to flooding-based ad-hoc routing protocols such as DSR, AODV and TORA.

Under an assumption that a mobile computer M has already achieved distance $|MM_{i+1}|$, when a wireless signal carrying a data message is transmitted from M_i, M takes place of M_i and re-transmits the wireless signal if the following conditions are satisfied:

[Surrogate Re-transmission Conditions]

(1) M receives the data message correctly.

(2) M_{i+1} does not receive the data message correctly.

(3) M is the nearest mobile computer to M_{i+1} among mobile computers satisfying the above condition (1).□

M detects satisfaction of the condition (2) by not receiving an Ack control message from M_{i+1} before timer expiration. If M_{i+1} correctly receives a data message, M_{i+1} sends back to an Ack control message to M_i after a SIFS interval and M overhears it. In order for M to check satisfaction of the condition (3), each neighbor mobile computer M sets the following timer on receipt of a data message.

$$W_M = |MM_{i+1}|/|M_iM_{i+1}| \times (DIFS - SIFS) \quad (3)$$

After receipt of a data message, M waits for a SIFS interval and W_M. If M receives an Ack control message from one of neighbor mobile computers including M_{i+1} receiving the data message correctly during the waiting time interval, it is not needed for M to take place of M_i, i.e. it is not needed for M to re-transmit the data message to M_{i+1}. This is because the data message is correctly received by M_{i+1} if the Ack

control message is from M_{i+1} and the data message is going to be re-transmitted by another mobile computer from which the Ack control message is transmitted since it is nearer to M_{i+1} than M and has a shorter timer expiration interval otherwise. Otherwise, i.e. if M does not receive an Ack control message from other mobile computers including M_{i+1} during the waiting time interval SIFS+W_M, M takes place of M_{i+1} and sends back an Ack control message to M_i. Neighbor computers of M including M_i and others receiving the data message is notified that M is the nearest mobile computer to M_{i+1} correctly receiving the data message and it is not required for them to re-transmit the data message since M takes place of M_i and re-transmits it.

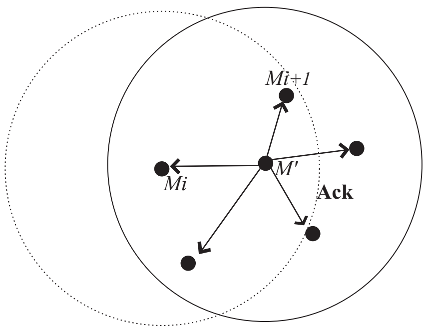

Fig. 2. Surrogate Re-transmission of Ack (Notification to Neighbors).

In this method, an Ack control message transmitted from M is not always received by all neighbor mobile computers receiving a data message transmitted from M_i. Multiple mobile computers between which it is impossible to transmit messages directly may take place of M_{i+1} and M_i simultaneously, i.e. transmit Ack control messages and re-transmit the data messages. In this case, according to CSMA/CA and RTS/CTS mechanism, one of them re-transmits the data message first which may not be the nearest mobile computer to M_{i+1} among neighbor mobile computers correctly receiving it. However, $|MM_{i+1}| < |M_iM_{i+1}|$ is surely satisfied and higher probability of successful transmission and shorter transmission delay are achieved.

Even in case that timers expires in multiple mobile computers without receiving an Ack control message from another mobile computer since the Ack control message is lost and is not received correctly, by receiving a re-transmitted data message and an Ack control message for the re-transmitted data message, it is possible for the other mobile computers to cancel their schedule to re-transmit the data message. Hence, only duplicate Ack control messages are additional communication overhead. On the other hand, an Ack control message transmitted from one of neighbor mobile computers is not received by some others due to locations of the mobile computers. For example in Figure 3, though both mobile computers M'_p and M'_q are in a wireless signal transmission ranges of M_i and M_{i+1}, M'_p and M'_q are out of a wireless transmission range of each other. It may possible that both M'_p and M'_q receive a data message from M_i correctly and only M_{i+1} fails to receive it. Here, both M'_p and M'_q transmit Ack control messages due to no receipt of Ack control messages from neighbor mobile computers including M_{i+1}. By receiving these Ack control messages, M_i is notified not to re-transmit the data message due to proposal of surrogate re-transmission from M'_p and M'_q. However, M'_p and M'_q schedule re-transmission of the data message since Ack control messages are unreachable between them. In this case, one of them for instance M'_p retransmits the data message before M'_q and the data message is also not received by M'_q. Since an Ack control message for it is transmitted from M_{i+1} or a neighbor mobile computer and is received by both M'_p and M'_q, it is possible for M'_q to cancel its re-transmission schedule and to reduce additional communication overhead.

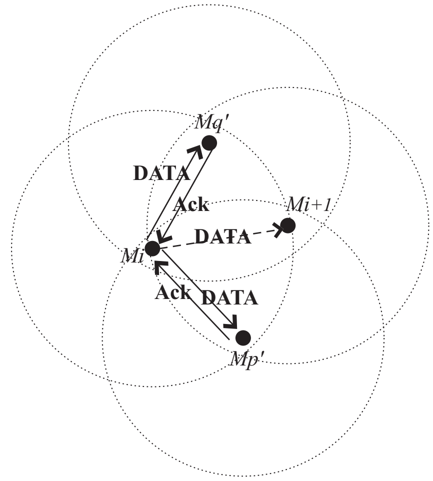

Fig. 3. Re-transmission Schedule in Multiple Neighbors.

According to the above dynamic addition of intermediate mobile computer by surrogate re-transmission, a mobile computer M is inserted into a multihop transmission route R between intermediate mobile computers M_i and M_{i+1}. Here, M may be included in wireless transmission ranges of the other intermediate mobile computers $M_j (i + 1 < j \leq n)$ in R. In this case, M forwards a data message not to M_i but to M_j as shown in Figure 4. Here, mobile computers $M_k (i + 1 \leq k < j)$ are dynamically removed from R and shorter transmission delay is achieved.

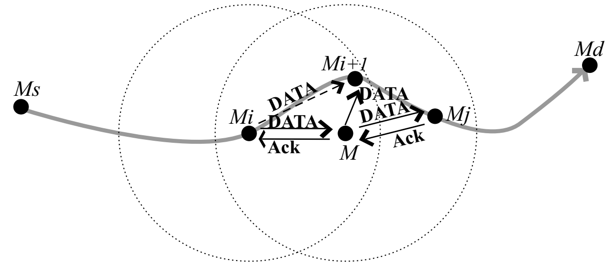

Fig. 4. Dynamic Removal of Intermediate Mobile Computers.

The proposed modification of wireless multihop transmission, i.e. addition and removal of intermediate mobile computers, is applied based on message-by-message manner. That is, the route modification is not permanent but temporary according to results of one-hop message transmission through a wireless link.

A. Protocols

B. Routing Protocol

In order to realize the surrogate re-transmission proposed in the previous section, all neighbor mobile computers of all intermediate mobile computers and a destination one in a wireless multihop transmission route $R = \|M_0 \ldots M_n\rangle\rangle$ have to achieve distance to neighboring mobile computers in R. The distance is needed to determine a timer expiration interval. In the following routing protocol the distance is achieved by the neighbor mobile computers by overhearing an *Rrep* message unicasted along R with predetermined, e.g. the maximum, transmission power. The following routing protocol is designed based on AODV routing protocol.

[Routing Protocol]

1) A source mobile computer M_0 broadcasts an *Rreq* message to all neighbor mobile computers within a wireless signal transmission range with the maximum transmission power.
2) On receipt of the first *Rreq* message from a neighbor mobile computer M_p, M_q entries M_p into its routing table as a next hop mobile computer to M_0 and broadcasts the received *Rreq* message to all neighbor mobile computers within a wireless signal transmission range with the maximum transmission power. M_q discards receiving *Rreq* messages from other neighbor mobile computers.
3) On receipt of the first *Rreq* message from a neighbor mobile computer M_p, a destination mobile computer M_n entries M_p as a next hop mobile computer to M_0 and unicasts an $Rrep$ message to M_p with the maximum transmission power.
4) On receipt of an *Rrep* message from a neighbor mobile computer M_r, M_q entries a tuple $\langle M_n, M_r, |M_qM_r|, hop\rangle$ where M_n is a destination mobile computer, M_r is a next hop mobile computer to M_n, $|M_qM_r|$ is distance between M_q and M_r calculated by receipt power of the $Rrep$ message and hop is a hop count from M_q to M_n achieved from the *Rrep* message. Then, M_q unicasts the $Rrep$ message to a next hop mobile computer M_p to M_0 with the maximum transmission power.
5) On receipt of an *Rrep* message from a neighbor mobile computer M_r, M_0 entries a tuple $\langle M_n, M_r, |M_0M_r|, hop\rangle$ where M_n is a destination mobile computer, M_r is a next hop mobile computer to M_n and $|M_0M_r|$ is distance between M_0 and M_r calculated by receipt power of the *Rrep* message and hop is a hop count from M_0 to M_n achieved from the *Rrep* message.
6) On receipt of the an *Rrep* message unicasted from M_r to M_p, M_q entries a tuple $\langle M_n, M_r, |M_qM_r|, hop\rangle$ where M_n is a destination mobile computer, M_r is a next hop mobile computer to M_n, $|M_qM_r|$ is distance between M_q and M_r calculated by receipt power of the $Rrep$ message and hop is a hop count from M_q to M_r achieved from the $Rrep$ message. □

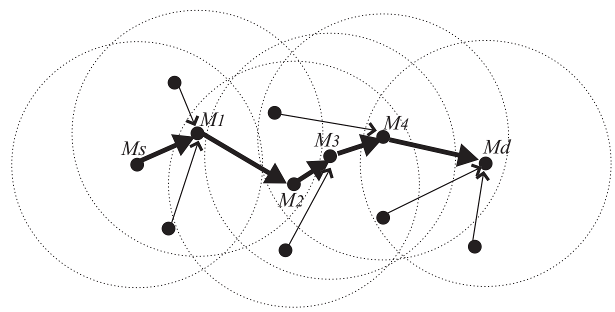

Fig. 5. Next Hop Setting in Routing Protocol.

Figure 5 shows an example in which a wireless multihop message transmission route R from $M_s(= M_0)$ to $M_d(= M_5)$ is detected and all neighbor mobile computers of $\{M_1, \ldots, M_5\}$ set a next hop mobile computer in their routing table for surrogate re-transmission. If a neighbor mobile computer overhears multiple *Rrep* message, it selects a next hop mobile computer, i.e. it unicasts a data message to a mobile computer, from which an *Rrep* message with the minimum hop counts from M_d.

C. Data Transmission Protocol

Based on routing tables achieved by a routing protocol designed in 3.1, a data message transmission protocol with dynamic addition and deletion of intermediate mobile computers is designed as follows.

[Data Transmission Protocol]

1) A source mobile computer M_0 unicasts a data message to a next hop mobile computer M_1 according to a routing table entry with a destination mobile computer M_n. $|M_0M_1|$ is piggybacked to the data message.
2) On receipt of the data message, an intermediate mobile computer M_i unicasts an Ack control message to M_{i-1} after a SIFS interval. In addition, M_i unicasts the received data message to a next hop mobile computer M_{i+1} according to a routing table entry with a destination mobile computer M_n. $|M_iM_{i+1}|$ is piggybacked to the data message.
3) On receipt of a data message from M_{i-1}, a mobile computer M within a wireless signal transmission range of M_{i-1} searches a routing table entry $\langle M_n, M_i, |MM_i|, hop\rangle$. If there is no such an entry, M discards the received data message. Otherwise, i.e. if such an entry exists in a routing table, if $|MM_i| \geq |M_{i-1}M_i|$ where $|M_{i-1}M_i|$ is piggybacked to the received data message, M also discards the received data message. Otherwise, i.e. if $|MM_i| < |M_{i-1}M_i|$, M sets a timer T whose expiration time is $|MM_i|/|M_{i-1}M_i| \times (DIFS - SIFS)$ after a SIFS interval.

3-1) If M receives an Ack control message transmitted from a neighbor mobile computer before expiration of T, M discards the data message and resets T.

3-2) If T expires without receipt of an Ack control message, M unicasts an Ack control message to M_{i-1} by taking place of M_i. Then, M unicasts the received data message to M_k where $\langle M_n, M_k, |MM_k|, hop\rangle$ is included in a routing table with the minimum hop.

4) If a mobile computer M_i on a multihop transmission route R or M out of R which has unicast a data message and is waiting for an Ack control message receives an Ack control message before a DIFS interval, it completes a data message transmission in this hop. Otherwise, i.e. if it passes a DIFS interval without receipt of an Ack control message, it re-transmits the data message.

5) After a SIFS interval, a destination mobile computer M_n unicasts an Ack control message to M_{n-1}. □

III. Evaluation

In this section, we show results of performance evaluation of our proposed method in simulation. First, reduction of numbers of retransmission in one-hop wireless transmission is evaluated in simulation experiments. Here, $N-2$ mobile computers are randomly located according to randomization on unique distribution in a circle field centered by a transmitter mobile computer M_t and whose radius is 100m. In addition, a receiver mobile computer M_r is located in the circle where $|M_tM_r| = x$. In this simulation assumption, a data message is transmitted from M_t to M_r. If $N = 2$, only M_t and M_r are located in the simulation field.

Here, probability of failure transmission of a message is assumed to be based on distance l from a transmitter mobile computer to a receiver one as follows (Figure 6):

$$f(l) = \begin{cases} 0 & (0 \le l \le \bar{l}) \\ (l-\bar{l})/(100-\bar{l}) & (\bar{l} \le l \le 100) \end{cases}$$

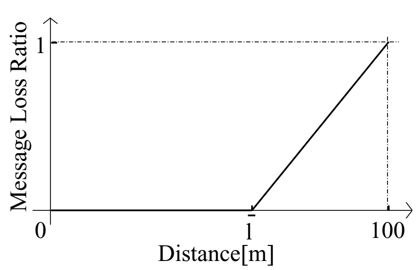

Fig. 6. Message Loss Model in Simulation.

We measure transmission delay from M_t to M_r in simulation time and achieve the results as shown in Figure 7 where $\bar{l}$:= 0m, 20m, 40m, 60m and 80m. Figure 7 shows reduction ratio of transmission delay against the conventional one-hop transmission without surrogate re-transmission (N=2). Shorter transmission delay is achieved in higher density of mobile computers, i.e. more neighbor mobile computers, and the performance improvement is saturated in N=20 environments. Here, only 87.1% shorter transmission delay is required for one-hop wireless transmission.

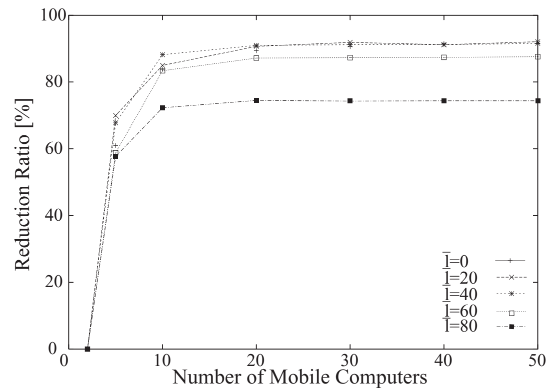

Fig. 7. Reduction Ratio of 1-hop Transmission Delay.

In data message transmission protocols with Ack control messages for confirmation of receipt of data messages and suspension of re-transmission, i.e. including both the conventional and the proposed protocols, Ack control messages are also lost in transmission. Hence, even after a receiver mobile computer successfully receives a data message, a transmitter mobile computer may continue to transmit it. Hence, we evaluate required time duration and numbers of transmitted data and control messages until transmission of a data message is stopped, i.e. data message transmission protocol in this one-hop transmission is completed. Figures 8 and 9 are simulation results for various numbers of mobile computers same as the previous simulation. Here, the number of data and control messages are 98.2% reduced and 99.1% shorter time is required to complete the transmission protocol where N=20. Hence, our proposed surrogate re-transmission mechanism also reduces time and communication overhead.

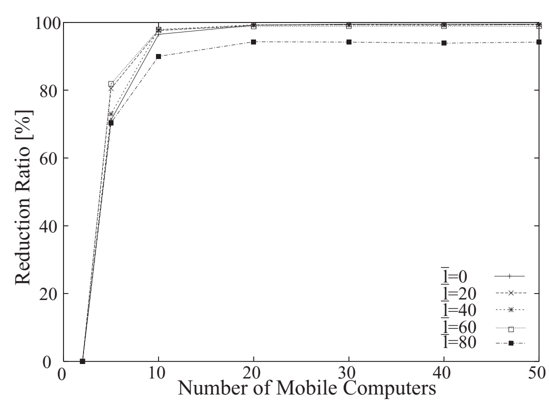

Fig. 8. Reduction Ratio of Numbers of Control Messages.

Next, we show results of performance evaluation of MMDTP in wireless multihop data message transmission. Here, 50–400 mobile computers are randomly located according to unique distribution randomness in a 1000m×1000m

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2009 proceedings.

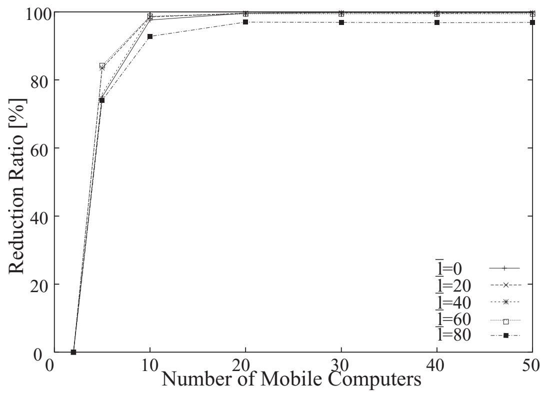

Fig. 9. Reduction Ratio of Protocol Execution Time.

square field. A wireless signal transmission range of each mobile computer is a 100m radius circle and message loss ratio is modeled same as the previous one-hop simulation with $\bar{l}$:=60m. Reduction of end-to-end transmission delay by applying MMDTP compared to the conventional multihop transmission without surrogate re-transmission is shown in Figure 10. By MMDTP, 3.3-45% shorter transmission delay is required in MMDTP and the reduction ratio is higher in environments with higher density of mobile computers.

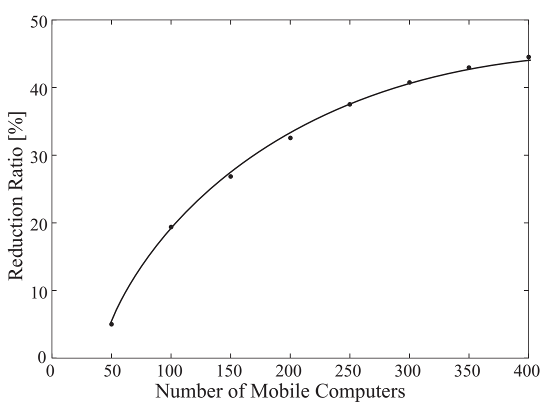

Fig. 10. Transmission Delay Reduction in Multihop Transmission.

IV. Concluding Remarks

This paper proposes a data message transmission method along a wireless multihop message transmission with dynamic addition and deletion of intermediate mobile computers to the route detected by an ad-hoc routing protocol in message-by-message manner according to result of one-hop message transmission. Both a message transmission protocol with surrogate re-transmission and skip of intermediate mobile computers and a routing protocol for achieving distance information used by the data transmission protocol are designed. Simulation results show that the proposed method achieves more than 90% shorter message transmission delay, more than 90% control message reduction and more than 90% shorter protocol time in one-hop transmission. In addition, 5–45% shorter transmission delay is realized in wireless multihop transmission even with contentions and collisions of wireless signals. The time reduction is caused by both surrogate re-transmission and skip of intermediate mobile computers and the authors will analyze their efficiency in detail.

References

[1] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," Standard IEEE 802.11 (1997).
[2] "Wireless MAC and PHY Specifications for Wireless Personal Area Networks," Standard IEEE 802.15.1 (2002).
[3] Basagni, S., Chlamtac, I., Syrotiuk, V.R. and Woodward, B.A., "A Distance Routing Effect Algorithm for Mobility," Proceedings of the International Conference on Mobile Computing and Networking, pp. 76–84 (1998).
[4] Datta, S., Stojmenovic, I. and Wu, J., "Internal Node and Shortcut Based Routing with Guaranteed Delivery in Wireless Networks," Proceedings of the IEEE International Conference on Distributed Computing and Systems, pp. 461–466 (2001).
[5] David B. Johnson, David A. Maltz, Yih-Chun Hu and Jorjeta G. Jetcheva Johnson, D.B., Maltz, D.A., Hu, Y.C., and Jetcheva, J.G., "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks," Internet Draft, draft-ietf-manet-dsr-04.txt (2000).
[6] Jacquet, P., Muhlethaler, P., Clausen, T., Laouiti, A., Qayyum, A. and Viennot, L., "Optimized Link State Routing Protocol for Ad Hoc Networks," Proceedings of IEEE International Publication, pp. 62–68 (2001).
[7] Karp, B. and Kung, H.T., "GPSR: Greedy Perimeter Stateless Routing for Wireless," Proceedings of the 6th Annual International Conference on Mobile Computing and Networking, pp. 243–254 (2000).
[8] Park, V. and Corson, S., "Temporally-Ordered Routing Algorithm (TORA) Version 1 Functional Specification," Internet Draft, draft-ietf-manet-tora-spec-04.txt (2001).
[9] Perkins, C.E. and Bhagwat, P., "Highly Dynamic Destination-Sequenced Distance Vector Routing (DSDV) for Mobile Computers," Proceedings. of ACM SIGCOMM'94, pp. 234–244 (1994).
[10] Perkins, C.E. and Royer, E.M., "Ad-hoc On-Demand Distance Vector Routing," Proceedings of IEEE Workshop on Mobile Computing Systems and Applications, pp. 99–100 (1999).
[11] Prosenjit, B. and Pat, M., "Routing with Guaranteed Delivery in Ad Hoc Wireless Networks," Wireless Networks, No. 7, pp. 609–616 (2001).
[12] Urrutia, J., "Two Problems on Discrete and Computational Geometry," Proceedings of the Japan Conference on Discrete and Computational Geometry, pp. 42–52 (1999).