MTFR: Mobility Tolerant Firework Routing

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Abstract—In this paper, we propose a novel mobility assisted, adaptive broadcast routing mechanism called *Mobility Tolerant Firework Routing* (MTFR) that improves node reachability especially in situations with high mobility. We evaluate our proposal by simulations with the random walk and random waypoint mobility models and disclose tendencies that can be observed with regard to typical parameters for wireless communication. As a result, we show that our proposed method produces better reachability in many aspects at the expense of a small additional transmission delay and intermittent traffic overhead, as well as some specific nonrecoverable conditions are revealed due to wireless coverage density. Hence, an extension with adaptive parameter management has the potential to produce even better reachability and we thus consider MTFR to be a promising routing protocol, feasible enough for future Internet infrastructures.

Keywords-Firework routing; potential based routing; future Internet; mobility models; wireless reachability

I. INTRODUCTION

Recently there has been increased research activity on future Internet infrastructures among researchers in the field of ICT (Information and Communication Technology) and new basic principles of network management are currently being developed. From the viewpoint of the societal requirements toward a prosperous future, one goal of the future Internet is to pursue and guarantee its reliability and efficiency at the same time. In addition, ubiquitous mobility and wireless communication are anticipated to play an even more essential role in the future. In other words, flexibility and simplicity of mobile network management will bring us a more comfortable life at the cost of an increase in management complexity. Hence, when designing new network protocols and architectures, it is very important to take reliability and efficiency into consideration.

Infrastructure-free systems of *Mobile Ad hoc Networks* (MANET) are very flexible under unstable network connectivity situations, for example in natural disasters, and they can cope with dynamic network topology changes caused by mobility of the nodes. Potential-based routing is one of the promising technologies to accomplish MANET-like routing in an autonomous manner. There have been several proposals for carrying out potential routing and exchanging potential information autonomously among nodes in their vicinity is the common basic approach for most of these protocols. Therefore, the time until convergence of potential updates is reached, as well as the assurance of node reachability are suitable indicators for the performance of these routing protocols.

Each potential routing scheme has its own benefits. However, as far as we know, few of them can deal with situations of highly changing topology caused by geographic movement of nodes. Therefore, we focus on mobility oriented extensions of potential routing in order to improve the data transmission reachability. In our approach, a data replication scheme like broadcast transmission is introduced to improve reachability. In addition, in order to avoid unnecessary broadcast traffic, the potential value is utilized as a measure for selection of broadcasters. The potential value of a node is an indicator on how close the destination is from the current node and therefore it is well suited as appropriate node selection procedure. We first investigate and reveal basic tendencies and advantages of our approach from the viewpoint of efficient wireless communication. Then, we pay special attention to the relationship between transmission reachability and wireless coverage. With the above results, it is discussed that our approach has the capability of constructing a more sophisticated autonomous system.

The rest of this paper is organized as follows. In Section II we discuss related work. Then, in Section III we first explain the basic mechanism of potential based routing before describing our proposed firework routing mechanism in detail. In Section IV, the performance of our proposal is compared with conventional potential routing (link-diversity routing) for the random walk and random waypoint mobility models using computer simulations. Finally, Section V summarizes our results and concludes this paper.

II. RELATED WORK

Among the first studies on potential based routing, Basu et al. [1] proposed *potential based routing* (PBR) as traffic-aware routing method. The potential of each node and edge is calculated from both distance and traffic volume information with a weighting factor. The authors showed that PBR works well in a slowly varying traffic situation, but did not present any results on the adaptation to dynamic traffic

conditions. Following their work, several other researchers proposed variations of potential based routing.

Baumann et al. [2] proposed HEAT using anycast routing for wireless mesh networks. HEAT assumes a potential analogous to thermal conductivity. This conductivity level is exchanged among neighboring nodes and used as an indicator for traffic routing. Similarly, Lenders et al. [3] proposed link-diversity routing using the FDMR (*Finite Difference Method Routing*) algorithm, which is also based on an analogy to heat levels, but has a more lightweight potential calculation scheme than HEAT. The nodes exchange their temperatures with their neighbors and the temperature difference between source and destination node is propagated over the network. The same authors also proposed a service query forwarding mechanism using potentials in [4]. This potential indicates the capacity of a service, such as printer speed or link capacity, and the query is forwarded toward the service that is most likely available. In [5] *Potential Management based Proactive Routing* (PMPR) is proposed, where nodes update their potential on demand leading to signaling cost reduction. In [6] *Parameterized Gradient Based Routing* (PGBR) is proposed, where the potential gradient is calculated in a stochastic manner using the load of both links and nodes. PGBR is described as possible application to IPTV services run by different operators on a single IP network infrastructure.

In terms of theoretical analysis, Toumpis et al. [7] proposed "packetostatics" and analyzed potential routing especially from the viewpoint of physics. They focused on traffic flows in a densely populated sensor network identical to an electrostatic field. The theoretical analysis of potential functions is discussed from the viewpoint of electromagnetic field analysis. In addition, Toumpis [8] also surveyed wireless sensor network management approaches based on the analogy with physics. Moreover, Bettstetter [9] analyzed the relationship between node density and graph connectivity, which provides theoretical approximations of PBR under static node placement.

In order to reinforce wireless transmission reachability, several approaches to extend broadcast range have been investigated. Sidera et al. [10] proposed DTFR (*Delay Tolerant Firework Routing*), which is a geographic routing protocol for wireless delay tolerant networks. DTFR consists of four phases. Data packets are first forwarded to a firework center (FC) that is closely located to the destination in the homing phase. Then packets are replicated to some copies in the explosion phase, travel to a firework endpoint closely located to the FC in the spread phase, and finally if the best route is found, the other unnecessary multihop route would be locked in lock phase. Hsu et al. [11] proposed an ad hoc routing protocol named FLARE, which constructs a candidate route in a cost-efficient manner when the current route is broken. In addition, Law et al. [12], [13] proposed *Fireworks*, an adaptive multicast/broadcast protocol to formulate group
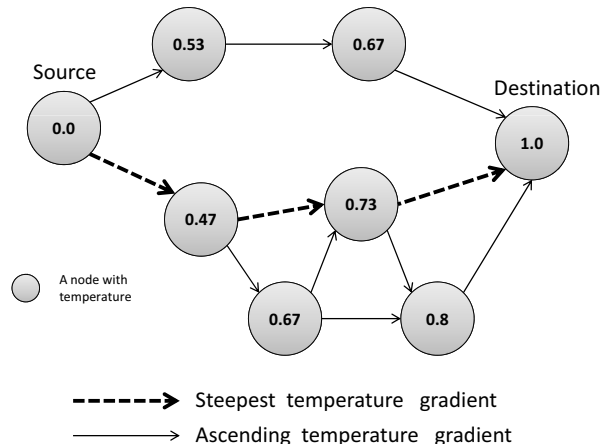

Figure 1. Temperature example in conventional potential routing (link-diversity routing)

member affinity named cohorts in an ad hoc manner. This type of efficient multicast/broadcast protocol can achieve cost reduction in terms of traffic overhead compared with always broadcast case.

As stated above, most of these potential routing methods have many benefits to achieve robustness, but usually their operation is assumed and evaluated for slow or non-mobility conditions. Mechanisms that operate well under highly dynamic traffic conditions while improving data transmission reachability are in our opinion a very important issue for the future Internet infrastructure.

III. PROPOSAL OF FIREWORK ROUTING PROTOCOL

In this section, we propose our novel extension of potential routing to improve node connectivity. First, we briefly discuss conventional potential routing with the example of link-diversity routing. Then we introduce our proposed mechanism and discuss protocol details.

A. Conventional Potential Routing

We now explain conventional potential routing for the example of link-diversity routing [3]. This routing scheme relies on a thermodynamic analogy and a typical network model is shown in Figure 1. Each node has its own temperature and iteratively exchanges it with neighbor nodes after which it updates its own temperature as

$$\phi_{t+1}(x_i) = \begin{cases} \dfrac{\sum\limits_{k \in nbr(x_i)} \phi_t(x_k)}{|nbr(x_i)|}, & |nbr(x_i)| > 0 \\ 0, & |nbr(x_i)| = 0 \end{cases}$$

where the network has the set of nodes $\{x_1, \cdots, x_n\}$, the set of neighbor nodes of x_i is expressed as $\{x_k; k \in nbr(x_i)\}$, and ϕ_t indicates the temperature of x_i at iteration step t. In addition, the temperature of the source node x_s and
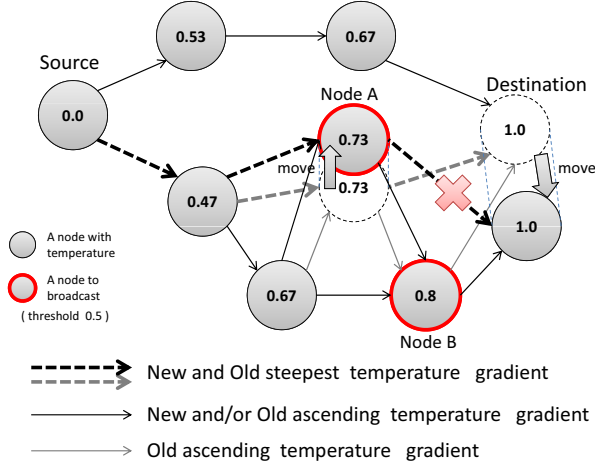
Figure 2. Explanation of mobility tolerant firework routing (MTFR)

destination node x_d are set constant and they have their own boundary conditions as follows.

$$\phi_t(x_s) = 0 \qquad \phi_t(x_d) = 1 \qquad \forall t \geq 0$$

After convergence of the temperature calculation, each intermediate node forwards packets toward its neighbor node which has the highest temperature. As a consequence, packets sent from the source node will reach the destination node along the steepest temperature gradient path as shown in Figure 1.

B. Mobility Tolerant Firework Routing (MTFR)

In our proposal, a *firework threshold* of the node temperature is introduced below which the node simply forwards packets and above which it broadcasts the packets until a hop count limit. This broadcast feature improves reachability and makes it possible to cope with highly dynamical topology changes. In addition, the temperature can be regarded as a relative distance to the destination, and therefore, defining the threshold is efficient from traffic load viewpoint. Due to the similarity to the branching part of fireworks, we call our mechanism *Mobility Tolerant Firework Routing* (MTFR).

Figure 2 shows a simple network example with MTFR. In this example, an intermediate node A with temperature value 0.73 and the destination node are assumed to be moving in the direction of each respective arrow. After both movements, the original last hop link between the destination and node A becomes disconnected and hence conventional potential routing would fail in such a situation. On the contrary, in the case of MTFR, node A with temperature 0.73 then broadcasts packets to all of its neighbors and therefore packets will continue reaching the destination via node B.

Algorithm 1 Firework routing protocol algorithm

1: Power on the device
2: Node initialization procedure
3: Establish links with neighboring nodes
4: Initial temperature calculation with all nodes before in-service
5: Collection of call condition
6: Call origination procedure
7: **for** communication time= $1, 2, ..., $ end time **do**
8:    **if** condition timer has expired **then**
9:       Collection of call condition
10:       Adjust "temperature update timer" according to status
11:       Adjust "hop limit number" according to status
12:       Adjust "condition update timer" according to status
13:    **end if**
14:    **if** temperature update timer has expired **then**
15:       **for** active link number= $1, 2, ..., n$ **do**
16:          Collection of TheirTemperature from all the neighbor nodes
17:          **if** any of TheirTemperatures has changed **then**
18:             Update MyTemperature
19:          **end if**
20:          **if** MyTemperature has changed **then**
21:             Send new MyTemperature
22:          **else if** MyTemperature is unchanged **then**
23:             Send short message to indicate "no-change"
24:          **else**
25:             System status failure
26:          **end if**
27:          Receive TheirTemperature message
28:       **end for**
29:    **end if**
30:    **if** there is a packet to be forwarded **then**
31:       **if** MyTemperature is greater than firework threshold **then**
32:          Broadcast packet to all the neighbors
33:       **else if** MyTemperature is less than threshold **then**
34:          Forward packet to highest temperature neighbor
35:       **end if**
36:    **end if**
37: **end for**
38: Call termination procedure

C. MTFR Protocol

In order to construct an actual implementation of MTFR, we should confirm that temperature exchange with neighbor nodes, temperature update exchange among neighbor nodes, and packet forwarding according to temperature are feasible. In this section, we explain our proposed MTFR protocol in detail. The protocol sequence is described in pseudocode in Algorithm 1 and mainly consists of three parts: system

Table I
BASIC SIMULATION PARAMETERS

parameter	value
initial layout	uniformly random in $10\,\text{km} \times 10\,\text{km}$ area
number of nodes	$2000 - 4000$
wireless range	$100 - 500\,\text{m}$
mobile node speed	1 m/s (pedestrian) 20 m/s (car) 100 m/s (bullet train)
firework hop limit	7 hops
firework threshold	0.5
mobility model	RWK RWP (constant speed, no pause)
simulation time	$100 - 300\,\text{sec}$

Figure 3. Influence of wireless transmission range on reachability

parameter revision procedure, temperature update procedure, and packet forwarding procedure. From Algorithm 1, preparations for in-service by a mobile node are done (lines 1-5) and communication is started (line 6). During the call busy state, the mobile node performs mainly three tasks periodically (line 7). First, the mobile node maintains several system management timers to update system parameters such as temperature update timer, hop limit update timer, and system condition timer. After the system condition timer has expired, the mobile node adjusts each system parameter value at the right time (line 8-13).

Second, if the temperature update timer expires, the mobile node starts temperature recalculation (line 14). Concerning each active link with neighbor nodes, their temperature values are collected (line 16) and the node's own temperature is recalculated with them (line 17). If its own temperature has changed after recalculation, the mobile node sends the new temperature to all its neighbor nodes (line 21) and if not, a short notification message indicating no change is sent (line 23). On the contrary, updated temperature messages from neighbor nodes are also received (line 27). Each node utilizes the sequence number in exchanging temperature messages for avoiding confusion among each node's update timing gap.

Third, the mobile node looks up the packet transmission table and sends packets to appropriate neighbor nodes according to its own temperature value (line 30). If the temperature is above the firework threshold, the packet will be sent to all neighbor nodes with greater temperature than its own (line 32) and if the temperature is under the firework threshold, the packet will be sent to the single neighbor node with the highest temperature (line 34). Different broadcast algorithms can be considered as well as defining another threshold to select nodes for broadcasting packets. Finally, the mobile node terminates the call (line 38). Our proposed mechanism and protocol are evaluated in the following section.
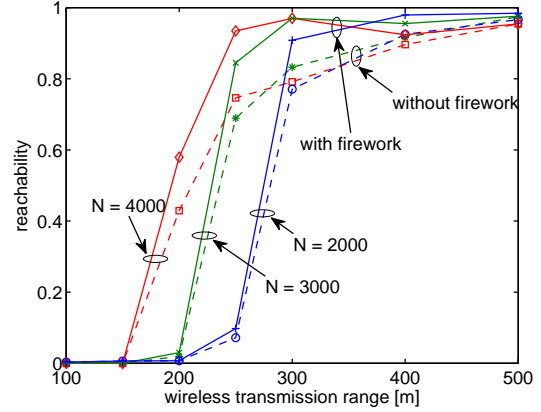
IV. NUMERICAL EVALUATION

In this section, we evaluate our proposed method by simulations using the random walk (RWK) and random waypoint (RWP) mobility models with nodes distributed initially uniformly random in a $10\,\text{km} \times 10\,\text{km}$ area. For comparison, we also show the results of link-diversity routing [3] denoted by "without firework" in the following figures. In RWP constant motion speed and no pause time at waypoint changes are assumed. Basic simulation parameters are listed in Table I. A firework temperature threshold value of 0.5 is used, as the obtained results showed in general good performance, but a more thorough analysis of the impact of this threshold is planned as future work. We implemented the protocols in our own simulation program in the C language and each simulation result is based on the average of hundred or more samples, so we omit showing confidence intervals. If not mentioned otherwise, the number of nodes is 4000, mobile speed is $100\,\text{m/s}$, firework hop limit is set to 7 hops, and simulation time is 100 sec.

A. Effects of Wireless Coverage

In this section, we investigate the basic tendency of the firework effect on the influence of packet reachability with different number of nodes and wireless transmission ranges. Figure 3 shows the reachability probability over wireless transmission range for the RWK mobility model.

From Figure 3, we can conclude in general that the packet reachability improves with the number of nodes and with the wireless transmission range. This is because increasing both values brings us a wider wireless coverage area for packet transmission. MTFR is able to restore reachability almost completely to that of theoretically maximum possible without mobility. In addition, we can see S-shaped curves at some specific wireless transmission range in all cases. Wireless transmission range is effective on node density at a power of 2, which produces a stronger relationship with reachability than the number of nodes. Therefore, a
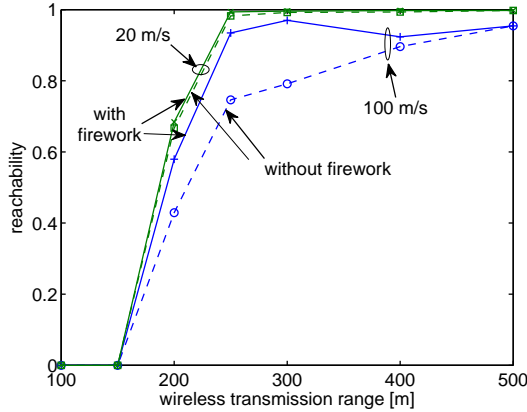
Figure 4.　Influence of vehicular speed on reachability

Figure 5.　Reachability improvement under different mobility models

steep increase appears in the curves for certain transmission ranges.

It is also observed that there are some unrecoverable conditions in certain densely populated cases like 4000 nodes and over 400 m wireless range. Here, the firework improvement effect corresponds to the difference in reachability between results obtained with and without firework. This is because the increase of possible edges with more neighbors has the side effect of increasing the hop counts, which eliminates the firework effect by the hop number limit. In conclusion, there is an optimal point with number of nodes and wireless transmission range for reachability improvement under some specific conditions.

B. Impact of Vehicular Speed

We now investigate the tendency against mobile node speed. Figure 4 shows that for low speeds (20 m/s or less) no firework effects are observed. The curves for 1 m/s are not shown here as they coincide with those for 20 m/s speed. However, for higher speed of 100 m/s quite large effects of around 0.2 improvement compared to without firework begin to appear. The reason for this lies in the increased vehicular speed, which produces on average larger movement distances. Therefore, the higher the mobile node's speed is, the larger the firework effects are.

C. Influence from Node Mobility Model

Next, we analyze the influence of the mobility model on our method using RWK and RWP. For comparison purposes, we now show on the y-axis of the following figures the improvement of reachability of the results with firework over without firework instead of absolute reachability values. The improvement of reachability indicates the phenomenon that the firework process turns initially unreachable conditions into reachable ones. The improvement in reachability by the firework method at the speed of 1 m/s is shown in Figure 5. In the case of RWK, almost no effect from firework
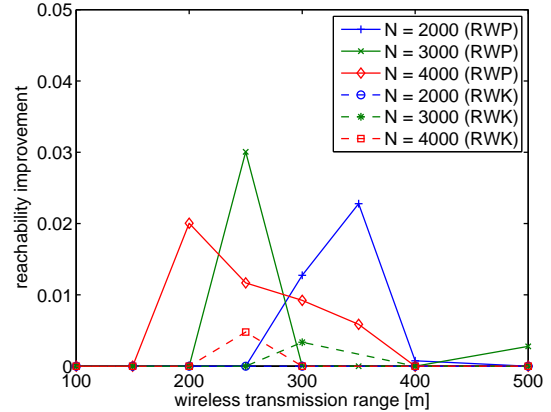
is visible, but significant improvements by firework are observed in the case of RWP even at the speed of 1 m/s irrespective of the number of nodes.

This tendency can be explained by the average movement distance by mobile nodes. The traversed distance is larger in RWP than RWK due to its directional movement and therefore the probability becomes higher to get out of reach of wireless coverage. In order to compare average movement distance in both random walk mobility and fixed one directional walk (ODW) mobility, it has been reported [14] that the average distance of each movement $w_{\mathrm{RWK}}(t)$ and $w_{\mathrm{ODW}}(t)$ after time t passed can be expressed as

$$E\left[w_{\mathrm{RWK}}(t)\right] = \sqrt{t} \qquad \text{and} \qquad E\left[w_{\mathrm{ODW}}(t)\right] = t$$

where ODW implies the motion where mobile nodes move along a straight-line with constant speed, which is comparable to the ideal case of the random waypoint mobility with no pause time. Therefore, from the above two equations, it can be concluded that movement in RWK generates less average movement distance than RWP and as a consequence reachability improvement in RWP becomes larger than in RWK.

D. Effects of Temperature Update Time Interval

In this section, we show the simulation results for different simulation time. Figure 6 shows the reachability improvement when simulation time is 100, 200, and 300 sec with 4000 nodes at the speed of 1 m/s under RWP. Since we adopt a sufficient convergence threshold value to quickly restore the perfectly recovered state after temperature convergence, the simulation time is equivalent to the temperature update time interval. This equivalence is explained by considering repeated simulations and temperature calculation by turns. From Figure 6, the increase of the temperature update time interval results in a greater improvement of reachability of the destination node. This firework effect is due to the
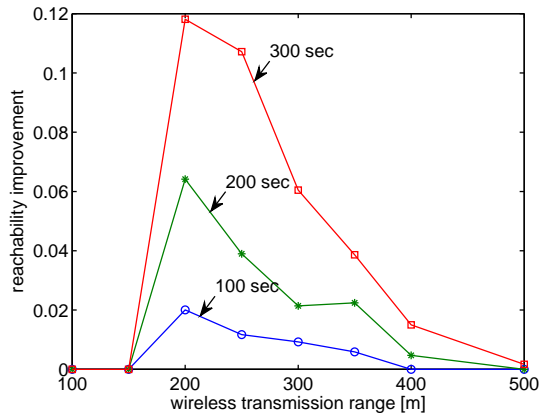
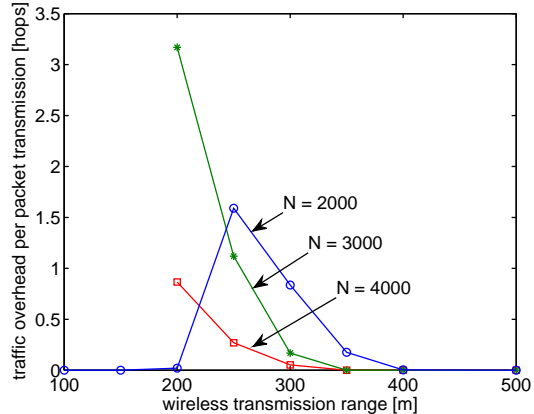Figure 6.   Reachability improvement over temperature update time interval

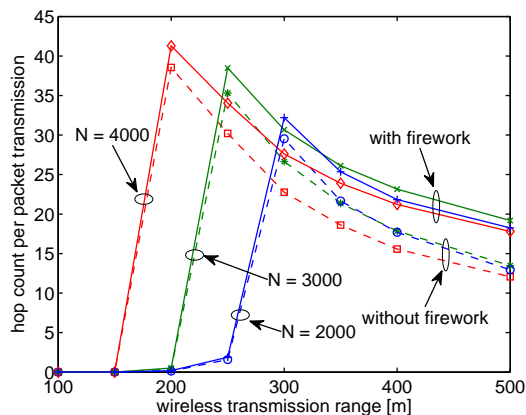Figure 8.   Traffic overhead analysis

Figure 7.   Transmission delay analysis

F. Evaluation of Traffic Overhead

Finally, we analyze the tendency from the viewpoint of traffic overhead accompanied by the firework procedure. Figure 8 shows simulation results of additional traffic overhead by firework with different numbers of nodes under RWK at the speed of 100 m/s and with different wireless ranges for packet transmission. Here, traffic overhead is defined as the total number of hops traveled by transmitted packets and normalized by the number of nodes and total amount of reachability recovery. From Figure 8, at higher wireless transmission ranges, such as more than 350 m, there is not much difference between the results with and without firework. However, for the middle wireless transmission ranges from 200 m to 350 m, additional traffic overhead by firework is observed but it is less than 3.5 hops. In addition, at lower wireless transmission ranges such as less than 200 m, there is again no difference between results with and without firework due to the poor reachability in both cases.

Even though firework routing requires in the medium range cases additional traffic overhead, reachability recovery has greater importance over overhead increase in future network infrastructures, since it allows a connection to the destination compared to without firework where no connection can be made at all. Moreover, here in our simulation, we use a fixed firework threshold of 0.5 and the higher our utilized firework threshold is, the less additional traffic overhead is produced. We can also easily embed some additional intelligence to reduce the overhead by avoiding unwanted replicated packets, for example, by not broadcasting packets to nodes that have a low expectation of recovery due to their temperature or vehicular motion. As a consequence, the above results can be seen as worst case scenario and indicate that firework routing inevitably produces an increase of traffic overhead to some extent, but the benefits of higher connectivity with MTFR outweigh this drawback to make it feasible enough for an actual system implementation.

same reason of increasing communication opportunities as explained in Section IV-A.

E. Evaluation of Transmission Delay

Figure 7 shows simulation results of end-to-end transmission delays in terms of hop count per a packet transmission generated with different numbers of nodes under RWK at the speed of 20 m/s and with different ranges for packet transmission. At smaller wireless ranges, transmission delays are observed as almost zero in all conditions due to the lack of reachability and at larger wireless ranges, delays are converged to around 15-20 hops in all conditions due to almost full reachability. In middle wireless ranges, we can recognize some additional transmission delays due to the firework procedure. However, from Figure 7, it turns out that delay differences between results with and without firework are limited to less than 6 hops in all cases. This fact indicates that our MTFR is feasible enough for operation in real communication scenarios. As a result, MTFR produces better reachability at the expense of a small additional transmission delay from overall viewpoint.

V. Conclusion

In this paper, we proposed a novel mobility assisted firework routing mechanism named Mobility Tolerant Firework Routing to improve packet reachability and we evaluated it by simulations with the the random walk and the random waypoint mobility models. First, we studied our proposal from the wireless coverage viewpoint. It turned out that our method showed a great improvement in reachability by the firework effect and the increase in wireless coverage resulted in general in a larger reachability. Next, we analyzed the behavior from vehicular speed viewpoint and an increase in speed was confirmed to promote an improvement in reachability. In addition, from the analysis of the mobility model, we could see that the reachability improvement in RWP was greater than that in RWK. Furthermore, longer temperature update time intervals produced larger improvement effects due to the average movement distance. Finally, we showed the analysis results from the viewpoint of end-to-end transmission delay and traffic overhead. It was shown that our method produces better reachability at the expense of an additional transmission delay and some of this traffic overhead is expected to be further reduced by adding simple extensions. From the above discussion, we confirmed that our proposed method is feasible and produces better reachability than standard potential-based routing mechanisms. Additionally, by extending the methods with an adaptive parameter management system, we consider MTFR to have the capability to further improve reachability and to become a better candidate for a safe and secure social future Internet infrastructure.

References

[1] A. Basu, A. Lin, and S. Ramanathan, "Routing using potentials: a dynamic traffic-aware routing algorithm," in *Proceedings of ACM SIGCOMM, 2003*, pp. 188–191, August 2003.

[2] R. Baumann, S. Heimlicher, V. Lenders, and M. May, "HEAT: Scalable routing in wireless mesh networks using temperature fields," in *Proceedings of IEEE Symposium on a World of Wireless, Mobile and Multimedia Networks, 2007 (WoWMoM'07)*, June 2007.

[3] V. Lenders and R. Baumann, "Link-diversity routing: A robust routing paradigm for mobile ad hoc networks," in *Proceedings of IEEE International Conference Wireless Communications and Networking Conference, 2008 (WCNC '08)*, vol. 1, March 2008.

[4] V. Lenders, M. May, and B. Plattner, "Service discovery in mobile ad hoc networks: A field theoretic approach," *Pervasive and Mobile Computing*, vol. 1, pp. pp.343–370, 2005.

[5] D. Y. Kwon, J.-H. Chung, T. Suh, W. G. Lee, and K. Hur, "A potential based routing protocol for mobile ad hoc networks," in *Proceedings of 11th IEEE International Conference on High Performance Computing and Communications, 2009 (HPCC '09)*, June 2009.

[6] S. Balasubramaniam, J. Mineraud, P. McDonagh, P. Perry, L. Murphy, W. Donnelly, and D. Botvich, "An evaluation of parameterized gradient based routing with QoE monitoring for multiple IPTV providers," *IEEE Transactions on Broadcasting*, vol. 57, pp. 183–194, June 2011.

[7] S. Toumpis and L. Tassiulas, "Packetostatics: Deployment of massively dense sensor networks as an electrostatics problem," in *Proceedings of IEEE International Conference on Computer Communications, 2005 (INFOCOM '05)*, March 2005.

[8] S. Toumpis, "Mother nature knows best: A survey of recent results on wireless networks based on analogies with physics'," *Computer Networks*, vol. 52-2, pp. pp.360–383, February 2008.

[9] C. Bettstetter, "On the minimum node degree and connectivity of a wireless multihop network," in *Proceedings of ACM International Symposium on Mobile Ad Hoc Networking and Computing, 2002 (MobiHoc' 02)*, pp. 80–91, June 2002.

[10] A. Sidera and S. Toumpis, "DTFR: A geographic routing protocol for wireless delay tolerant networks," in *10th IEEE IFIP Annual Mediterranean Ad Hoc Networking Workshop 2011 (MedHocNet '11)*, June 2011.

[11] C.-C. Hsu and C.-L. Lei, "Firework search for location aided routing enhancement in mobile ad-hoc networks," in *Proc. of the 8th ACM international workshop on Mobility management and wireless, 2010 (MobiWac '10)*, October 2010.

[12] L. K. Law, S. V. Krishnamurthy, and M. Faloutsos, "A novel adaptive protocol for lightweight efficient multicasting in ad hoc networks," *International Journal of Computer and Telecommunications Networking*, vol. 51-3, February 2007.

[13] L. K. Law, S. V. Krishnamurthy, and M. Faloutsos, "Fireworks: An adaptive group communications protocol for mobile ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 6-3, March 2007.

[14] T. Hattori, *Random Walk and Renormalization (*in Japanese*)*. Kyoritsu Publishing, August 2004.