A CHECKPOINT BASED MESSAGE FORWARDING APPROACH FOR OPPORTUNISTIC COMMUNICATION

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ABSTRACT

In a Delay Tolerant Network (DTN), the nodes have intermittent connectivity and complete path(s) between the source and destination may not exist. The communication takes place opportunistically when any two nodes enter the effective range. One of the major challenges in DTNs is message forwarding when a sender must select a best neighbor that has the highest probability of forwarding the message to the actual destination. However, finding an appropriate route remains an NP-hard problem. This paper presents a concept of Checkpoint (CP) based message forwarding in DTNs. The CPs are autonomous high-end wireless devices with large buffer storage and are responsible for temporarily storing the messages to be forwarded. The CPs are deployed at various places within the city parameter that are covered by bus routes and where human meeting frequencies are higher. For the simulative analysis a synthetic human mobility model in ONE simulator is constructed for the city of Fargo, ND, USA. The model is tested over various DTN routing protocols and the results indicate that using CP overlay over the existing DTN architecture significantly decreases message delivery time as well as buffer usage.

INTRODUCTION

Delay Tolerant Networks (DTNs) are designed to provide delay tolerant communication when there are no end-to-end paths among the nodes and when the network topology changes continuously. The communication of messages takes place in DTNs whenever the nodes opportunistically make contact. Therefore, a node may have to store the messages and wait until the next node is close enough to start the transfer and eventually the message is delivered to the final destination. Due to the lack of end to end connectivity and dynamic topology, the traditional ad hoc routing protocols such as AODV (Johnson and Maltz 1996) and DSR (Perkins and Royer 1999) cannot be applied to DTNs. Therefore, significant research (e.g., Khan *et al.* 2011; Burgess *et al*. 2006; Shinya *et al*. 2011) is carried out in designing routing protocols for DTNs that must tackle unpredictable network environments. Generally, the message forwarding in DTNs is classified as: (a) uninformed and (b) informed forwarding.

In the uninformed approach, nodes do not utilize any existing knowledge and forward messages to neighbors in range, until the messages are finally delivered to their destinations. The aforementioned knowledge can be a meeting probability, mobility pattern, and current direction. To increase message delivery ratio, the nodes in uninformed approach generate and spread the multiple copies of messages. Among popular algorithms, two such techniques are *Epidemic Routing* (Vahdat and Becker 2000) and *Spray and Wait* (Thrasyvoulos *et al*. 2005). As, the uninformed approach uses flooding to propagate maximum messages, the advantage is the higher probability of successful message delivery to destination. A major drawback of uninformed approach is the higher consumption of network resources and buffer. Moreover, there is no guarantee that flooding the network will have messages delivered to the destination.

The nodes in the informed forwarding approach use previous knowledge and heuristics to select suitable nodes to which messages are forwarded for delivering to the destination. The idea is to decrease the number of message flooding in the network, while maintaining an acceptable level of message delivery ratio. Certain parameters may be utilized to make an optimal selection of candidate nodes. Some of the parameters are, but not limited to, node's history of encounters e.g. *PRoPHET* (Lindgren *et al*. 2003), *MaxProp* (Burgess *et al*. 2006), *MV* (Burns *et al*. 2005), mobility pattern (Cacciapuoti, *et al*. 2012; Leguay *et al*. 2005) and frequency of visiting certain places (Ghosh *et al*. 2006), *Message Ferrying* (Zhao *et al*. 2004), and *Data Mules* (Almasaeid and Kamal 2008). All of the aforementioned protocols make use of some kind of available knowledge to improve overall message delivery ratio. However, there is a tradeoff between the improved message delivery and higher consumption of network resources. To make a good choice in selection of forwarding node, a node has to store information of various parameters about other nodes. For example, in (Lindgren *et al*. 2003) each node maintains a history of contacts with all other nodes in the area. When a node encounters more than one node simultaneously, only the node that has maximum number of contacts would be selected for message forwarding. In limited scenarios, the aforementioned protocol(s) may show higher performance. However, in the real-life large scale networks, with the nodes having limited buffer and processing capabilities, the performance of DTN routing protocols may degrade significantly with increasing nodes.

This paper presents an idea of CP based message forwarding approach. Apart from having own memory and processing capabilities, each CP is a node that represents a specific region on the city map and may maintain the information of geographic locations of all the other CPs. However, in contrast to the existing work, the CPs are not communication dependent on any fixed backbone network, and can be easily relocated. The simulation results indicate that the use of CPs reduce the processing overhead and buffer utilization in predicting the locations of the destination nodes in DTNs.

The rest of the paper is organized as follows. First, related work is described with a comparison to the CP approach. Next, the CP architecture is discussed along with simulation scenario. Finally, the simulation results are discussed with conclusion and future work.

RELATED WORK

For many years human mobility has been an active area of research in DTNs. It has been shown through various experiments that human populations follow repeated mobility patterns. Different methods have been applied to collect the human mobility traces. For example (Rhee *et al*. 2011) studied the urban human mobility through GPS traces. The authors in (Cacciapuoti, *et al*. 2012) used the signaling information in cell phones through the AirSage (www.airsage.com) technology to gather the mobility traces, and (Balazinska and Castro 2003) used PDAs and laptops interacting with access points at various locations in an office building to observe the mobility pattern. All the previous studies reveal that humans tend to follow a repetitive schedule of meetings at same places and times, and the human mobility is predictable following a power law distribution. The aforementioned fact is further endorsed by (Song *et al*. 2010) that human mobility is 93% predictable.

Therefore, CP based approach presented in this paper is inspired by the same fact that humans tend to follow schedule of meetings with higher interaction probabilities at commonly visited places such as bus stops/stations and shopping malls where the CPs may be deployed. The aforementioned technique may shift the buffer overheads from nodes to CPs in making the predictions about the destination node's location and next meeting times. In the DTNs context, an approach that involves some sort of location information is categorized as *location-based routing.*

In the past, various techniques have been presented for location-based routing in DTNs. The authors of *MV* (Meeting and Visits) (Burns *et al*. 2005) proposed a message exchange mechanism in pairwise contacts among peers that depends on the history of previous encounters and the visits of nodes to particular geographic locations. *MV* assumes that peers have infinite buffer space. In (Zhao *et al*. 2006), the authors presented algorithms for optimal deployment of *Throw Boxes* that are stationary wireless nodes to relay the messages among the mobile nodes. However, in this paper, we deploy the checkpoints on a real city map to determine the effect of human mobility in DTN based message forwarding. Similarly, Virtual Segment (VS) by (Shinya *et al*. 2011) and TACO-DTN by (Sollazzo *et al*. 2007) are similar techniques that have access points connected with the fixed backbone network installed at various geographic locations and the interconnectivity among the access points is provided through mobile nodes. The aforementioned approach is dissimilar to CP approach presented here as there is no mandatory physical connection of CPs with backbone network and CPs can be easily relocated (e.g. in disaster situations). However, the CPs may be connected with backbone to act as hotspots for Internet. In the next section we discuss the CP architecture.

CHECKPOINT ARCHITECTURE

The major components of the CP architecture include static CP nodes, mobile wireless nodes, buses, and additional components (e.g. Internet connected Access Points) that may be integrated with CP architecture.

CP Nodes

A CP is a wireless node that can be any low cost custom design hardware. The basic components of a CP node are but not limited to processor, memory, solar powered batteries, multiple interfaces (Standard Ethernet, 802.11b/g/n, Bluetooth), GPS, and storage. Each CP may optionally have the record of GPS coordinates of other CPs in the area. The coordinates are relayed through mobile nodes to the neighboring CPs along with normal data packets. Moreover, we assume that the CPs can be reconfigured with various DTN routing protocols. For example, if routing protocol used by CP is *PRoPHET*, then the CP maintains a database of recent encounters with mobile nodes for certain amount of time *T* after which the old data is overwritten to make space for new records. In addition to message routing, other tasks that may be assigned to CP include content distribution at specific intervals such as travel information, promos, news and information caching. The main fields maintained in the database of each $Checkpoint_i$ are indicated in Table-1.

Table 1: Database fields for a $Checkpoint_i$

Node ID	The ID of a mobile node N_i
Number of contacts	The number of contacts a node made with $Checkpoint_i$
CP ID	CP with which the node made contacts. Here multiple entries are possible. Because, a node may make contacts with more than one CP.
Coordinates	The GPS coordinates of a CP last contacted by a node. This helps in synchronization of location information of CPs throughout the region.
Last Contact Time	Time of last contact with $Checkpoint_i$
Expected Contact Time	This time is predicted based on the node's history of contacts.

Mobile Nodes

The mobile nodes are pedestrians, cars, and buses with each node carrying 802.11b/g/n enabled wireless sets. This assumption makes sense due to a market research report (Technical Report 2009) according to which in year 2009 alone, a total of 144 million mobile phones were shipped with Wi-Fi capability and it is further estimated that such phones may reach 66% of the total shipments till 2015 (Technical Report 2010). In the CP approach, whenever a mobile node interacts with a CP, the mobile node shares database with the CP by sending a light weight summary vector and then the CP updates own database with new information about the node. Any two mobile nodes on encounter, exchange messages for storing, carrying, and forwarding, as well as the metadata of each node's visits to particular CPs. The minimum data structure required at each mobile node is reflected in Table-2.

Table 2: Database fields for a $MobileNode_i$

CPs	The IDs and coordinates of every CP a node has visited in past.
Number of Contacts	The number of contacts a node has made with each $Checkpoint_i$
Last Contact Time	Time of last contact with $Checkpoint_i$

Buses

Buses are the message carriers or relay nodes in CP architecture. Each bus follows a fixed route and schedule and may pass through more than one CP (bus stop) on predefined timings. Moreover, after every scheduled round, every bus returns to a central bus station. The buses may be installed with any custom made wireless hardware having communication and storage ability to store the received messages to be delivered to the destination CPs.

Message

The minimum fields a message may have are source address, destination address, destination CP address, and payload. To find the destination CP address, an online Google based custom map for CPs may be consulted that indicates the specific CPs deployed near a particular geographic location. The aforementioned map can be constructed temporally with the passage of time if the CPs relay their GPS coordinates along with the actual message.

Message Routing

The message forwarding in the presented approach depends on the DTN routing protocol the CP is configured with. If a CP utilizes encounter based routing, then source node uses mobility pattern and schedules of buses, to forward the packet to a CP that is located closer to the destination. As shown in Figure 1, there are four regions A, B, C, and X, each covered by a CP. Buses relay messages between any two regions and each bus also visits a central bus station denoted by X. The time of arrival and departure of buses is predefined. If a source node is within the communication range of CP, the node forwards a single copy of message to CP, to be relayed by bus nodes.

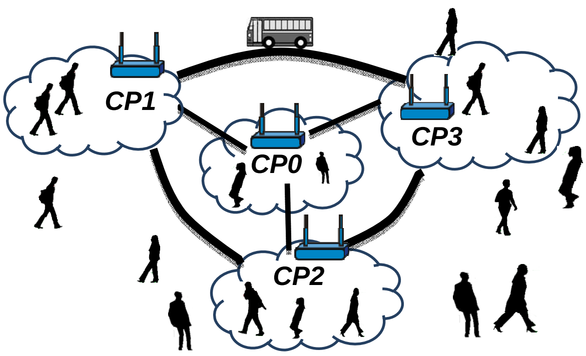

Figure 1: CP architecture with CPs connected through bus nodes.

However, if the source node is outside the communication range of CP, then the source node opportunistically forwards the packets to the neighboring nodes in an attempt to allow at least one copy of message to reach the nearest CP or to the final destination. The aforementioned message forwarding can be accomplished by utilizing any resource efficient replication based DTN protocol (e.g. *Spray and Wait*). The message copy is stored in a CP until the message is relayed to the next mobile node such as pedestrian, car, or bus. As the CPs are deployed on places where human mobility is higher, this increases the chance of message delivery to the destination. However, if CPs are deployed randomly (e.g. in case of post disaster scenario), then the GPS coordinates may be utilized in the calculation of minimum length routes among the source and destination CPs. There might be the case that a packet's destination information is not present in a CPs database. In that case, the destination is searched on the other CPs until the message TTL expires or all the CPs are searched.

SIMULATION

The simulation tool selected for the evaluation of the proposed CP model is ONE simulator (Keränen *et al.* 2009) which has rich features available for simulating DTNs with numerous mobility models. The map of Fargo city is exported from www.openstreetmap.org. Using open source GIS tool OPENJUMP, the map is post-processed and marked with various locations such as shops, homes, offices, meeting points, NDSU, and GTC bus station. Mobile nodes are divided into several groups and assigned to various locations on the map.

Scenario

For simulation, an area of 4 x 3 KM of the city of Fargo, ND, USA is selected as indicated in Figure 2. The buses are tagged with route numbers and follow various schedules available on the Metro Area Transit website (www.matbus.com). Each bus route has stops at various locations. At some of the stops the CPs are deployed, each identified with an ID and representing a geographic location within 100 meters radius. *CP5* is located in the central bus station where each route bus arrives or departs from. Two main shopping locations (West Acres and Walmart) are covered by *CP9* and *CP10* through which route 15 bus runs. Moreover, *CP1, CP2,* and *CP3* are installed at junctions that are not covered by any bus route and the messages are relayed among the CPs with the help of public automobiles. The human mobile nodes are Wi-Fi/Bluetooth devices that are distributed throughout the simulation area. As an example of the current scenario, if *CP4* receives a message to be relayed, *CP4* stores the message and waits for route 13 bus to arrive. On arrival, bus 13 relays the message to the central bus station where the message is received by *CP5*. *CP5* checks the message destination in database and routes the message to the final destination's CP. If no such entry is found, the message is routed to all the CPs after setting a TTL, on expiry of which, the message is deleted if not delivered (depending on the routing protocol).

Simulation Parameters

For the simulation, various combinations of parameters with range of values are selected. The simulation world is Fargo city map. Table 3 indicates the selected simulation parameters.

Table 3: Simulation parameters used in ONE.

Parameter	**Value**
World size	4250, 3900 m
Simulation time per run	43200s == 12h
Bluetooth Interface transmit rate	250kbps
Bluetooth interface transmit range	10 m
High speed interface type	Broadcast Interface
High speed interface transmit speed	10Mbps
High speed interface range	100 m
Total number of node groups in the scenario	21
Nodes mobility model	Map based movement
Car / pedestrians nodes buffer size	250Mb
Car / pedestrians wait times	0, 120 s
Car / pedestrians speed range	0.5 to 1.5 m/s
Car / pedestrian node interface	Bluetooth
Message TTL	300 min
Bus nodes buffer size	500Mb
Bus nodes wait time	10, 30 s
Bus nodes speed	7, 10 m/s
Bus nodes interfaces	Bluetooth and High speed
Cars nodes speed range	2.7, 13.9 m/s
Total Checkpoints	11
Checkpoints buffer size	500Mb
Checkpoints interfaces	Bluetooth and High speed
Events interval	45, 55 s
Message size range	500KB – 1MB
Total message generating nodes	78
Warm up period	1000 s

RESULTS

To perform model evaluation, a series of simulations have been performed in ONE Simulator. A single simulation time is 12 hours (43200s). The warm-up period is 1000s that is required for each CP and mobile node to have sufficient information in database. The CP architecture is evaluated for: (a) message delivery ratio, (b) buffer utilization, and (c) average message delay. The number of messages, CPs, buses, mobility pattern, nodes speed, transmission range, number of messages, and buffer sizes are altered in each simulation run to analyze the effect on average message delivery ratio, buffer utilization, and delivery delay.

Effect of CP deployment on average delay and message delivery ratio

One of the most important and challenging task is the selection of ideal places for the deployment of CPs.

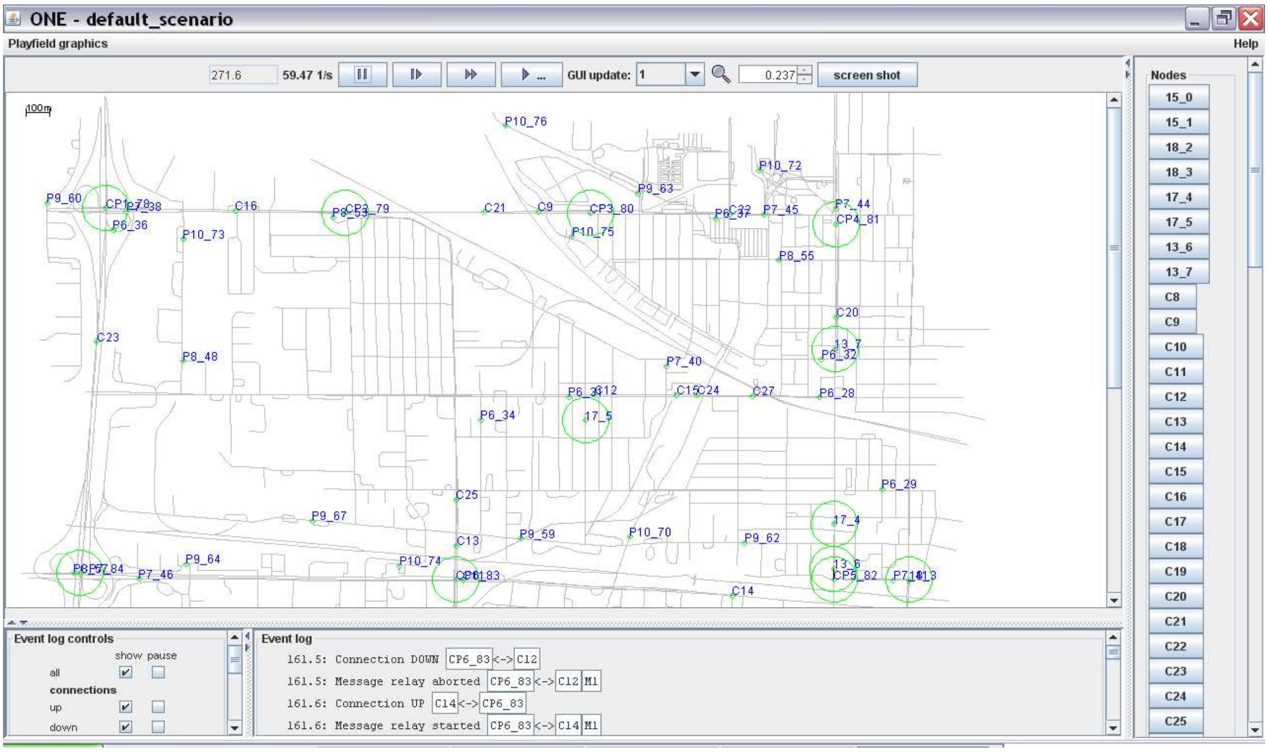

Figure 2: Checkpoint based simulation model in ONE, with circles representing the deployed CPs.

Several factors influence the selection of an ideal location (Khan 2007) and the most important is the human meetings frequency at a particular place. To examine the effect of CPs deployment, *CP1*, *CP7*, and *CP11* are deployed at locations where meeting frequencies are lesser, as compared to *CP4*, *CP5*, *CP6*, *CP9*, and *CP10* that are located at shopping malls, bus stations, and North Dakota State University (NDSU). The simulation is run multiple times to observe the effect of CP deployment on message delivery ratio. The results in Figure 3 indicate that for *CP1*, *CP7*, and *CP11* the message delivery ratio is lesser as compared to *CP5*, *CP6*, and *CP9* that are deployed considering the higher probability of meetings at these places. Therefore, the CPs would have more desirable outcomes if human mobility and meeting schedules are exploited before deployment.

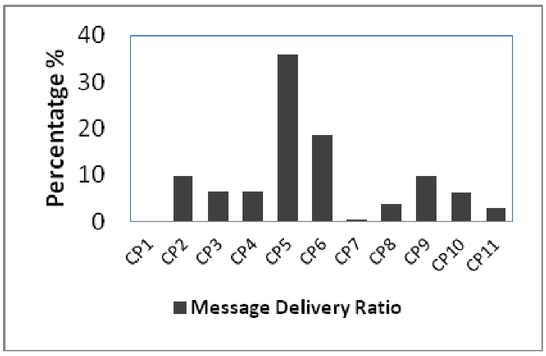

Figure 3: Effect of CP deployment on message delivery ratio.

Effects of the number of CPs on message delivery ratio and average delay

The effect of the number of CPs is observed on message delivery ratio and average delay in Figure 4. The test is run by increasing number of CPs while keeping number of buses and mobile nodes constant.

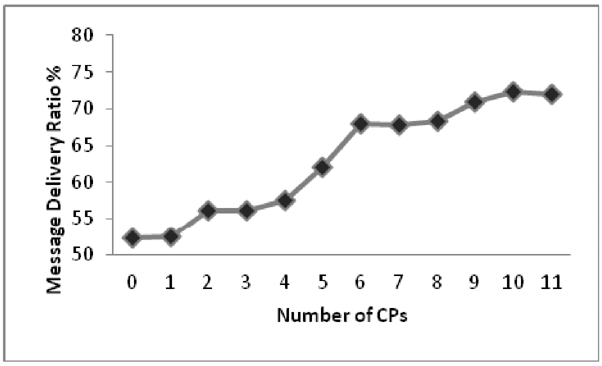

Figure 4(a): Effect of CPs on message delivery ratio.

From Figure 4(a) we can see that message delivery ratio improves by increasing number of checkpoints in the area. In Figure 4(b) we can observe that there is no significant decrease in packet latency until CP 5 is deployed. When CP 5 is deployed on bus station, there is remarkable decrease in packet latency as all the buses visit the common place. Therefore, due to the increase in human meetings at a common point, the packet latency also decreases.

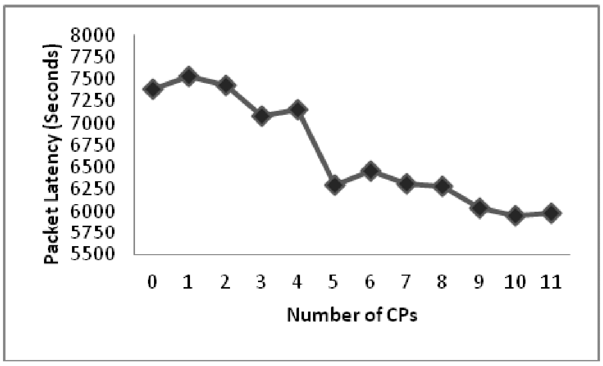

Figure 4(b): Effect of CPs on packet latency.

CP model evaluation with human mobility pattern

A place, where human meeting frequency is higher and repetitive, will be having higher message delivery probability. In such case DTN routing protocol such as *PRoPHET* would be more effective, as compared to the other routing protocols (e.g. *Spray and Wait* and *Epidemic*) that do not consider the node encounters pattern in making routing decisions. To evaluate the effect of human mobility on DTN routing, we identified some areas on the map as meeting points, where people tend to visit more frequently, and deployed a few checkpoints on these locations. Examples of such areas are shopping malls and main bus station GTC. We compared the performance of the three aforementioned routing protocols in terms of message delivery ratio and packet latency to investigate the effect of human mobility on these protocols. The simulation is run with same number of nodes for all three protocols and the results are indicated in Table 4.

Table 4: Performance of DTN protocols for human mobility.

	PRoPHET	Spray and Wait	Epidemic
Delivery Ratio %	71.90	62.39	73.51
Overhead ratio	27.64	7.52	34.77
Latency Avg. (s)	5964.51	5609.17	6163.54
Buffer time Avg. (s)	10249.51	16347.72	10225.18

In Table 4, latency avg. is average message delay from creation to delivery, overhead ratio is assessment of bandwidth efficiency, and buffer time avg. is average time the messages stayed in the buffer at each node. It can be observed that *Epidemic* routing has slightly higher delivery ratio as compared to *PRoPHET*. This is due to the fact that in *Epidemic* routing, the network is flooded with message copies such that each node replicates the message received and forwards to the next node. Therefore, the chances for message to reach the final destination also increase. However, from Table 4 we can see that message flooding increases bandwidth overhead ratio, and latency in *Epidemic* routing as compared to *PRoPHET* and *Spray and Wait* routing protocols. The buffer utilization time of *PRoPHET* is little higher than *Epidemic* as the message has to wait on a checkpoint before being delivered to the next mobile node (e.g. bus and car) towards the destination. The message delivery ratio is minimum for *Spray and Wait* routing due to the limit on number of message copies in the network and that leads to lower bandwidth overhead. Therefore, from Table 4 we can conclude that if human meeting schedules are exploited in message forwarding, then *PRoPHET* routing protocol surpasses the other two protocols in better performance.

CP model evaluation with RWP mobility pattern

To further examine the effect of mobility on DTN routing protocols, simulation is performed with a non-restricted random way point (RWP) mobility pattern. Such mobility pattern may be observed in post disaster scenarios, where people are moving from one relief camp to another and then back to disaster locations not following a specific mobility pattern. The evaluation of the three DTN protocols is performed by randomly placing 11 CPs with fixed number of mobile nodes having various speeds. Simulation is run to study the effect of random mobility on message latency, buffer utilization, and message delivery ratio. Table 5 shows the effect of random waypoint mobility.

Table 5: Performance of DTN protocols for RWP mobility

	PRoPHET	Spray and Wait	Epidemic
Delivery Ratio %	6.53	6.19	7.51
Overhead Ratio	37.42	22.05	44.68
Latency Avg. (s)	8705.82	8426.67	8661.85
Buffer time Avg. (s)	11451.37	14184.71	13090.77

From Table 5, we can observe that in random waypoint mobility, the message delivery ratio is significantly dropped. This is due to the fact that in random way point mobility, the frequency of nodes travel is higher towards the center of the map as compared to the map boundaries.

The aforementioned fact can be further verified by looking at Figure 5, which indicates that the message delivery ratio is higher at CP6 and C8, in all three protocols. Because, both the checkpoints (CP6 and CP8) are placed more closed towards the center of the map.

It can be further observed from Table 5 that there is no significant difference in the performance of the three protocols, as the *PRoPHET* cannot make use of human mobility pattern to forward messages towards the frequently visited points.

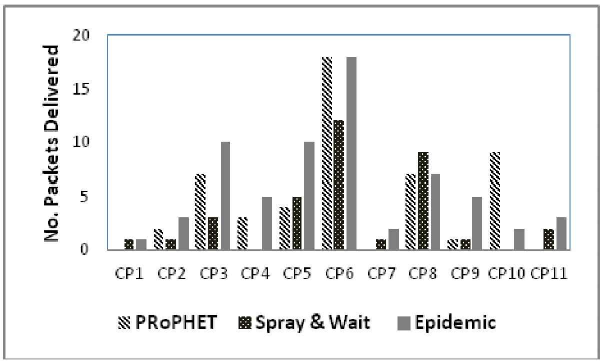

Figure 5: CP6 is located near center of map where nodes mobility is maximum.

CONCLUSIONS AND FUTURE WORK

In this paper, human mobility behavior is exploited to develop a CP based architecture, in which the CPs are deployed on locations where human meetings are more frequent and each CP is covering a specific geographic location in the city of Fargo, ND, USA. The messages are relayed among CPs through buses following fixed schedules. The simulation results indicate that by installing the CPs on locations with higher human interactions increase the predictability of finding the message destination. Therefore, the CP based approach improves message delivery ratio, decreases buffer utilization of nodes and message delivery time.

The future work includes the real test deployment of CP nodes in specific regions to further investigate their usability for message routing and content distribution which is among a few of the future applications of DTNs.

REFERENCES

Almasaeid, H.M. and A.E. Kamal. 2008. “Modeling mobility-assisted data collection in wireless sensor networks”. In *Proceedings of Global Telecommunications Conference 2008*. IEEE, 1-5.

Balazinska, M. and P. Castro. 2003. “Characterizing Mobility and Network Usage in a Corporate Wireless Local-Area Network”. In *Proceedings of 2003 MobiSys Conference.*

Burns, B.; O. Brock; and B.N. Levine. 2005. “MV routing and capacity building in disruption tolerant networks”. In *Proceedings of 2005 Infocom*. IEEE, 398-401.

Burgess, J.; B. Gallagher; D. Jensen; and B. Levine. 2006. “Maxprop: routing for vehicle-based disruption-tolerant networking”. In *Proceedings of 2006 infocom Conference.* IEEE, 1-11.

Cacciapuoti, A.S.; F. Calabrese; M. Caleffi; G. Di Lorenzo; and L. Paura. 2012. “Human mobility-enabled wireless networks for emergency communications during special events.” *Pervasive and Mobile Computing*, 2012.

Ghosh, J.; H.Q. Ngo; and C. Qiao. 2006. “Mobility profile based routing within intermittently connected mobile ad hoc networks (icman)”. In *Proceedings of the 2006 international conference on Wireless communications and mobile computing*. ACM, 551-556

Johnson, D.B. and D.A. Maltz. 1996. “Dynamic source routing in ad hoc wireless networks”. In *Proceedings of 1996 Mobile computing Conference*. 153-181.

Keränen, A.; J. Ott; and T. Kärkkäinen. 2009. “The ONE Simulator for DTN Protocol Evaluation.” In *Proceedings of SIMUTools, 2009, Rome, Italy.*

Khan, S.U.; T. Loukopoulos.; and H. Li. 2011. “Advances in Wireless, Mobile and P2P based Internet Protocols, Applications, and Architectures.” *International Journal of Internet Protocol Technology.* 6, No.1-2, 1-2.

Khan, S.U. 2007. “Approximate Optimal Sensor Placements in Grid Sensor Fields”. In *Proceedings of 65th Semi-annual IEEE Vehicular Technology Conference (VTC)*, Dublin, Ireland, April 2007, 248-251.

Leguay, J.; T. Friedman; and V. Conan. 2005. “DTN routing in a mobility pattern space”. In *ACM SIGCOMM workshop 2005 on delay tolerant networking and related topics.*

Lindgren, A.; A. Doria; and O. Schelen. 2003. “Probabilistic routing in intermittently connected networks”. In *SIGMOBILE mobile computing communications review.* 7, No.3, 19–20.

Perkins, C. and Royer, E. 1999. “Ad hoc on-demand distance vector routing.” In *2nd IEEE workshop on mobile computing systems and application.* IEEE. 90-100.

Rhee, I.; M. Shin; S. Hong; K. Lee; S.J. Kim; and S. Chong. 2011. “On the Levy-Walk Nature of Human Mobility Networking.” *IEEE/ACM Transaction*s. 19, No.3, 630-643.

Shinya, Y.; A. Nagataa; M. Tsurub; and H. Tamurab. 2011. “Virtual segment: Store–carry–forward relay-based support for wide-area non real-time data exchange.” *Simulation Modelling Practice and Theory*, 19, No.1, 30-46.

Sollazzo, G.; M. Musolesi; and C. Mascolo. 2007. “TACO-DTN: a time-aware content-based dissemination system for delay tolerant networks”. 2007. *Proceedings of the 1st international MobiSys workshop on Mobile opportunistic networking*, 83-90.

Song, C.; Z. Qu; N. Blumm; and A.L. Barabási. 2010. “Limits of Predictability in Human Mobility.” *Science Magzine.*, 327, No. 5968, 1018-1021.

Ionut, A. 2010. “Wi-fi enabled mobile phone handsets in the US, 2010-2015”. Technical report. Market research analysis, Coda Research Consultancy.

Ionut, A. 2009. “Wi-fi capable handsets: Residential and enterprise markets for wi-fi and dual-mode handsets”. 2009. Technical report, ABI Research.

Thrasyvoulos, S.; K. Psounis; C. S. Raghavendra. 2005. “Spray and wait: an efficient routing scheme for intermittently connected mobile networks” In *Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking.* ACM, New York, USA.

Vahdat, A. and D. Becker. 2000. “Epidemic routing for partially connected ad hoc networks”. Technical report. Duke University.

Zhao, W.; M. Ammar; and E. Zegura. 2004. “A message ferrying approach for data delivery in sparse mobile ad hoc networks”. In *Proceedings of MobiHoc, 2004.*

Zhao, W.; Y. Chen; M. Ammar; M. Corner; B. Levine; and E. Zegura. 2006. “Capacity Enhancement using Throwboxes in DTNs.” *International Conference on Mobile Adhoc and Sensor Systems (MASS)*. IEEE. Vancouver, BC, 31-40.