

Modeling Path Duration Time in Dynamic Convergecast Network

Zhijing Qin, Ye Zhao, Nalini Venkatasubramanian
 Donald Bren School of Information and Computer Science
 University of California, Irvine, USA
 {zhijingq, yez, nalini}@ics.uci.com

Abstract—Estimating communication latency is challenging in dynamic settings, e.g. mobile applications where the source and/or destination of the communication can move arbitrarily. In this paper, we explore a many-to-one communication pattern, called convergecast, where mobile sensors report their sensed values to one or more servers (data sinks) in a periodic or queried manner. Such "convergecast" communication is becoming increasingly relevant in sensor monitoring and pervasive sensing applications. An important aspect of enabling accurate collection is to ensure small delays in the collection process. The path duration, i.e. time between when a path from sensor to source is established and when it gets disrupted, is a key factor that affects end-to-end delay; much of the existing work on this topic is in the context of MANETs. We propose and evaluate a probabilistic model in convergecast to capture path duration times given models of the network/transmission, the scale of the network and mobility of network elements. We validate our model through simulations and verify that the proposed model can provide a reasonable representation for end-to-end delays in the convergecast network. Pervasive sensor networks of the future are likely to encompass multiple access technologies with varying network properties and transmission characteristics. The ability to model end-to-end network properties (such as path duration) can assist in improved utilization in such pervasive multinetworks.

I. INTRODUCTION

The explosion in the number of mobile devices and sensing platforms has caused a phenomenal increase in the amount of data available from diverse and multiple sources. Reliable and in-time data collection is critical for on-the-fly decision making in many time sensitive applications (e.g. quality aware data collection[3], surveillance video data collection[4] and health monitoring[5]). Protocols and systems for these applications use end-to-end delay as a key design and performance metric. Existing work has aimed to better understand how delays occur in mobile and sensor networks and how the delay scales with the number of nodes both via experimental observation and theoretical analysis.

Lately, the use of *convergecast* as a many-to-one communication has gained popularity in the design of wireless sensor network protocols[1][2]. Simultaneously, significant advances have been made in the MANET community to model delay properties of communication link, albeit in a one to one communication paradigm. Pioneering work [7], discovered that the capacity of a pure static ad hoc network will be limited as the number of nodes increases; adding a relatively small number base stations[8],[9], or mobile relay nodes [10] to a static ad hoc network can further enhance network capacity.

On examining delay from routing layer, we observe that path duration time(i.e. time between when a path from sensor to source is established and when it gets disrupted) is a critical parameter that affects the delay performance of a protocol. Generally speaking, the end-to-end delay of a routing protocol in an mobile network incorporates the route discovery time, data transmission time, route failure detection and recovery time - all of these factors are related to the path duration time. [11] first derived a link and path availability model for MANETs where nodes exhibit a random walk-based mobility. Further research provided detailed insights into availability characteristics of a general adhoc network by modeling link and path duration[12], given link dynamicity[13] and node speed and direction changes[14]. Path duration models have been used to predict link and route duration time and consequently used to design availability based routing protocol[15]. A typical issue that is of concern in convergecast networks are conflicts that arise when two children send data concurrently to their parent. Techniques usually focus on the time slot scheduling to avoid collision in the link layer. TDMA-based scheduling algorithms aim to minimize the time to complete convergecast, i.e. minimizing the latency [16][17]. In[18], algorithms are proposed to enable quick convergecast operations with minimum latency while complying with the ZigBee standard.

In this paper, we explore many-to-one convergecast communication paradigm for mobile sensor networks where mobile sensors report their sensing value to one or more sources, in routing layer. Specifically, we aim to develop a model to estimate path duration times in mobile sensing scenarios. Prior work in the MANET setting cannot be applied directly in the convergecast setting where additional dependencies exist due to the collection tree and its parent-child structure. We will present and evaluate a novel model in the following sections to overcome these limitations. The remainder of this paper is organized as follows: In section II, we articulate the network related models and assumptions in our analysis. Section III presents the details of our path duration time model. Simulation based validation is shown in section IV. We conclude in Section V with future research directions.

II. MODELS AND ASSUMPTIONS

A. Network Model

The network consists of N mobile sensor nodes and M static data sources all lying in a 2D unit square area (of side

length 1). The location of the static data sources are fixed, and uniformly distributed at random over the unit square area. The sensors periodically send data to a unique sink via stationary nodes. We assume the link between the sink and stationary nodes are stable. So in the following, we only consider path duration among stationary nodes and mobile nodes. And we will use data source and stationary node interchangeably. The mobile sensor nodes are distributed uniformly at random in the unit square area at time $t=0$. At later times their position and velocities are given by the mobility model described below.

B. Mobility model

Here we adopt random walk mobility model, which has been proved to be able to maintain the uniform distribution property[12]. Based on this model, each node's movement consists of a sequence of random length intervals called mobility epochs, during which a node moves at a randomly chosen velocity. A velocity is a vector with two elements: speed and direction. The speed is a random variable v , which is distributed uniformly between V_{min} and V_{max} . The direction is a random variable θ , which is distributed uniformly between 0 and 2π . We define the probability density function(PDF) of velocity as:

$$f_v(v, \theta) = f_v(v) \times f_v(\theta) = \begin{cases} \frac{1}{2\pi \times (V_{max} - V_{min})} & \text{if } v \in [V_{min}, V_{max}] \text{ and } \theta \in [0, 2\pi], \\ 0 & \text{Otherwise.} \end{cases} \quad (1)$$

C. Link duration time

If two nodes are within a constant communication range R (all nodes have the same R) of each other, we assume a bidirectional link exists between them. For simplicity we refer to bidirectional links as links for rest of this paper. The link between nodes MN_1 and MN_2 is on when the distance between nodes MN_1 and MN_2 is smaller than R and is down when this distance is bigger than R . The link duration is the interval between two successive on and down.

D. Other assumptions

1) *Transmission time scale is much smaller than moving time scale:* Due to the low speed of mobile nodes in our scenario, in this paper we focus on the link availability time inside only one epoch denoted as T_E . In other words, we assume the speed of the mobile nodes will not change once initiated.

2) *Small volume of data:* Since we focus on small amount of data such as network state information, we ignore the queuing delay in the routing node. This means that the End-to-End delay mainly consists of route discovery delay, route failure and recovery delay. Through this way we can obtain a direct correlation between End-to-End delay and path availability.

III. THEORETICAL ANALYSIS

In this section we derive analytical expressions for path duration time of our convergecast network scenario. First we will analyze the one hop path availability towards the data source, which serves as the basis for our further multi-hop cases in the second part.

A. One hop path duration time

As mentioned above, there are M static data sources uniformly distributed in the unit square area. Each data source dominates a sub square whose side length is $\Theta(\frac{1}{\sqrt{M}})$. We choose one such sub square to analyze the one hop path duration time. In this sub square, all mobile nodes send data to the dominator(static data source). When a mobile sensor node MN is about to enter a dominated area(on the boarder), the distance between MN and its dominator S is r . Based on r and transmission range R , and the velocity we can analyze the one hop link duration time of this mobile node. We assume the distance that MN traveled during the link duration period is l , as in Fig. 1. We have:

$$l(r, \theta) = 2\sqrt{R^2 - r^2 \sin^2 \theta} \quad (2)$$

$$r = \sqrt{(D/2)^2 + (D/2 - x)^2} \quad (3)$$

where D is the side length of the sub square and x is the initial position of MN in the border. We assume that x is uniformly distributed in $[0, D]$, which means the node can be at any point of the dominated area boarder with the same chance. When

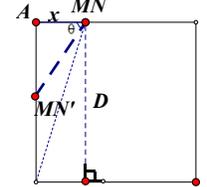
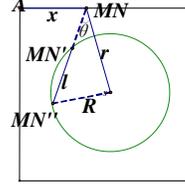


Fig. 1. One hop duration time Fig. 2. square area duration time

MN moves to MN' , the link is up while it moves to MN'' the link down. So we obtain the CDF (Cumulative Distribution Function) of the link duration time T , i.e $P(T \leq t)$:

$$F_t^{[1]}(t) = \int_0^D \int_{-\arcsin(R/r)}^{\arcsin(R/r)} \int_{V'_{min}}^{V_{max}} \frac{f_v(v, \theta)}{D} dv d\theta dx \quad (4)$$

where V'_{min} is the minimum required velocity from MN' to MN'' within time t :

$$V'_{min} = \frac{l(r, \theta)}{t} \quad (5)$$

So the PDF (Probability density function) of T can be obtained:

$$f_t^{[1]}(t) = \frac{\partial F_t^{[1]}(t)}{\partial t} \quad (6)$$

So the expectation of the one hop link duration time in one dominated area can be got:

$$E_t^{[1]}(t) = \int f_t^{[1]}(t) t dt \quad (7)$$

To evaluate the one hop link duration time under the different numbers of stationary nodes (different dominated area size), we need to analyze the average time that a mobile node moves across a dominated area whose side length is D . As show in Fig. 2, when $0 < \theta < \arctan(D/x)$,

$$k_1(x, \theta) = \frac{x}{\cos \theta} \quad (8)$$

while $\arctan(D/x) < \theta < \frac{\pi}{2}$

$$k_2(x, \theta) = \frac{D}{\cos(\frac{\pi}{2} - x)} \quad (9)$$

So assuming T_s as the time that a mobile node spends to cross a dominated area, the CDF (Cumulative Distribution Function)

of Ts, i.e $P(T_s \leq t)$:

$$F_{ts}(t) = \begin{cases} \int_0^D \int_0^{\arcsin(D/x)} \int_{\frac{k_1}{t}}^{V_{max}} \frac{f_v(v, \theta)}{D} dv d\theta dx \\ \int_0^D \int_{\arcsin(D/x)}^{\frac{\pi}{2}} \int_{\frac{k_2}{t}}^{V_{max}} \frac{f_v(v, \theta)}{D} dv d\theta dx \end{cases} \quad (10)$$

For $\frac{\pi}{2} < \theta < \pi$ case, it is the same as we described above. Accordingly, $f_{ts}(t)$ and $E_{ts}(t)$ can be got. Note D is determined by the number of the stationary nodes, namely M. The bigger M is, the more frequently a mobile node crosses a dominated area and the more likely a mobile node has a one hop link. So given length of the whole epoch, T_E , the average one hop duration time can be got by $\frac{E_t^{[1]}(t) * T_E}{E_{ts}(t)}$

B. Two-hop path duration time

Two hop path contains a one hop link from the stationary node to the relay node, as we discussed in the previous subsection, and a one hop link from the relay node to the mobile node. To analyze the link duration between two mobile nodes, relative velocity should be given first.

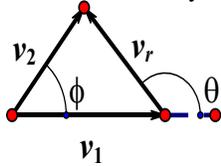


Fig. 3. Relative velocity

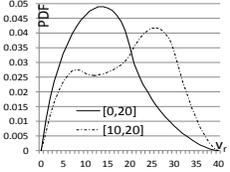


Fig. 5. Probability Density

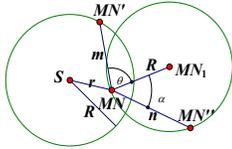


Fig. 4. two hop path duration time

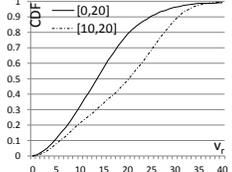


Fig. 6. Cumulative Distribution

1) *relative velocity of mobile nodes*: As shown in Fig. 3, similar with the concept in [15], the nodes' movement is centrosymmetric, we can assume v_1 is parallel to X-axis without lose of generality. Assuming mobile node MN_1 has a velocity $(v_1, 0)$, MN_2 has a velocity (v_2, ϕ) and their relative velocity is (v_r, θ) . Note the angel ϕ between v_1 and v_2 is uniformly distributed in $[0, \pi]$. And v_r has a angle θ , which is uniformly distributed in $[0, 2\pi]$. According to the cosine rule, we have:

$$v_r^2 = v_1^2 + v_2^2 - 2v_1v_2 \cos \phi \quad (11)$$

since θ , v_1, v_2 are independent, the PDF of the joint function is:

$$f_{v_1, v_2, \phi}(v_1, v_2, \phi) = f_v(v_1) f_v(v_2) f_\phi(\phi) = \frac{1}{\pi(v_{max} - v_{min})^2} \quad (12)$$

According to Jacobian transform, we have

$$f_{v_1, v_2, v_r}(v_1, v_2, v_r) = \frac{\partial \phi}{\partial v_r} f_{v_1, v_2, \phi}(v_1, v_2, \phi) \quad (13)$$

where

$$\frac{\partial \phi}{\partial v_r} = \frac{2v_r}{\sqrt{2v_1^2v_r^2 + 2v_2^2v_r^2 + 2v_1^2v_2^2 - v_r^4 - v_1^4 - v_2^4}} \quad (14)$$

Hence we get the PDF of the magnitude of the relative velocity:

$$f_{v_r}(v_r) = \int_{v_{min}}^{v_{max}} \int_{v_{min}}^{v_{max}} f_{v_1, v_2, v_r}(v_1, v_2, v_r) dv_1 dv_2 \quad (15)$$

Fig. 5 and Fig. 6 show the PDF and CDF of the relative velocity of $f_v(v, \theta)$ whose speeds are in the range of $[10, 20]$ and $[0, 20]$, respectively.

2) *Analytical expressions for two-hop path duration time*: Contrasted to pure ad hoc wireless network, in convergecast the path is established from the source(root) to the mobile node, like a tree. In data collection phase, a node always reports its data to its parent in the tree. So when a two-hop path is about to be established, the distance between the relay node and the mobile node are exact the transmission range R, while the distance between the source node and the relay node may be shorter than R, which means this one hop link is already on for some time. As shown in Fig. 4, when the path $S-MN-MN_1$ is established, the distance between MN and MN_1 must be R, while the distance between S and MN is $r < R$. Since we assume the mobile nodes are uniformly distributed in the experimental area, $f_r(r) = \frac{2r}{R^2}$. We use T, T_1, T_2 to denote the duration time of $S-MN-MN_1$, $S-MN$, and $MN-MN_1$, respectively. T is bigger than t if and only if T_1 and T_2 are bigger than t. So we have:

$$P\{T \leq t\} = 1 - P\{T_1 > t\} \times P\{T_2 > t\} \quad (16)$$

$$P\{T \leq t\} = 1 - (1 - P\{T_1 \leq t\}) \times (1 - P\{T_2 \leq t\}) \quad (17)$$

We use $F^{[2]}(t)$, $F_1(t)$ and $F_2(t)$ as the Cumulative Distribution Function of T, T_1 and T_2 . MN moves to MN' as a velocity of (v, θ) , total distance is m. So we can get:

$$F_1(t) = \int_0^R \int_0^{2\pi} \int_{\frac{m}{t}}^{V_{max}} f_v(v, \theta) f_r(r) dv d\theta dr \quad (18)$$

where

$$m(r, \theta) = \sqrt{R^2 - r^2 \sin^2 \theta} - r \cos \theta \quad (19)$$

so the PDF of T_1 is:

$$f_1(t) = \frac{\partial F_1(t)}{\partial t} \quad (20)$$

The CDF of T_2 is similar with T_1 . However, because MN and MN_1 are mobile nodes, we need to use relative velocity here. In addition, the start distance between MN and MN_1 is exact R. So we have:

$$F_2(t) = \int_0^{2\pi} \int_{\frac{R}{t}}^{V_{max}} f_{rv}(v) \frac{1}{2\pi} dv d\alpha \quad (21)$$

where

$$n(\alpha) = 2R \cos \alpha \quad (22)$$

so the PDF of T_2 is:

$$f_2(t) = \frac{\partial F_2(t)}{\partial t} \quad (23)$$

So the CDF of the two-hop path duration time T can be expressed as:

$$F_t^{[2]}(t) = 1 - (1 - F_1(t)) \times (1 - F_2(t)) \quad (24)$$

The PDF is:

$$f_t^{[2]}(t) = f_1(t)(1 - F_2(t)) + f_2(t)(1 - F_1(t)) \quad (25)$$

The expectation of two hop path duration time is:

$$\bar{E}_t^{[2]}(t) = \int f_t^{[2]}(t) t dt \quad (26)$$

Note there is a big difference between $E_t^{[1]}(t)$ and $\bar{E}_t^{[2]}(t)$. When we calculate $E_t^{[1]}(t)$, the start position of the mobile node is on the boarder of the dominated area, while in $\bar{E}_t^{[2]}(t)$

the start position is where a mobile node establishes a path towards source. The reason is that for one hop path, the link is always on right after the mobile nodes entering the transmission zone of the stationary node(ignoring the control message exchange time). But for two hop path, this is not the case. As shown in Fig. 7, there are two main prerequisites that

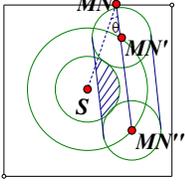


Fig. 7. two hops path in square

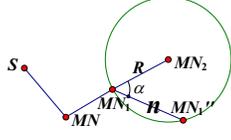


Fig. 8. three hops path

a mobile node has a two hop path towards to the stationary node: (a). This node crosses the ring area, $[R, 2R]$ (all nodes have the same transmission range). Note we only consider the ring area rather than the whole circle area with radius $2R$, because we also assume that if a node moves into the transmission range of the stationary node, it will change its two-hop path to one hop path immediately. (b). There is at least one other mobile node in the shadow area serving as a relay node. We can simply get the probability of a mobile node crossing the ring area, say P_a , using similar idea with the one hop case. Now we will show how to calculate the expectation of the probability that at least one relay node exists in the shadow area. Let S is size of the shadow area and $P\{\text{at least one node existing in } S\} = 1 - (\frac{1-S}{1})^{N-1}$ (all nodes are lying in an unit square area), where N is the total number of mobile nodes. Note we assume the whole environment area is a unit square area. S is a function of θ , as depicted in Fig. 7:

$$S(\theta) = \frac{2 \arccos(\frac{2R \sin \theta - R}{R})}{2\pi} \pi R^2 = R^2 \arccos(\frac{2R \sin \theta - R}{R}) \quad (27)$$

So given a variable $s, P\{S \leq s\} = p\{\theta > g(s)\}$, where $g(s)$ is the inverse function of $S(\theta)$. So:

$$F_s(s) = 1 - F_\theta(g(s)) = 1 - \int_{\frac{\pi}{6}}^{g(s)} \frac{1}{\pi} d\theta \quad (28)$$

$$f_s(s) = \frac{\partial F_s(s)}{\partial s} \quad (29)$$

So the Expectation of the probability that at least one node in shadow region,

$$E' = \int_0^{\frac{\pi * R^2}{2}} [1 - (\frac{1-S}{1})^{N-1}] f(s) ds \quad (30)$$

So the expectation of the new two-hop path duration time is

$$E^{[2]} = P_a E' \bar{E}_t^{[2]}(t) \quad (31)$$

C. Multihop path duration time

The expectation of n -hop path duration time can be got iteratively from the two-hop path case. Considering the characteristics of convergecast, a tree-like topology is always built from the root down to the leaves. In other words, when a node is about to join the tree, its parent already has a path towards to the root. So at the start of the path availability, each relay node has a distance $r (\leq R)$ away from its parent, while the leaf mobile node has a distance R from its parent

(R is the transmission range). Fig. 8 shows the case of a three hops path, and we will briefly describe how a three-hop path duration time can be calculated. Here we use $T^{[2]}$ and $T^{[3]}$ to denote the duration time of path $S - MN - MN_1$ and path $S - MN - MN_1 - MN_2$. Also we use T_3 to denote the duration time of link $MN_1 - MN_2$. We use $F^{[3]}(t)$ and $F_3(t)$ as the Cumulative Distribution Function of $T^{[3]}$ and T_3 . MN_1 moves to MN_1' as a velocity of (v, α) and the total distance is n . Similar with (21) we have:

$$F_3(t) = \int_0^{2\pi} \int_{\frac{n}{2}}^{V_{max}} f_{rv}(v) \frac{1}{2\pi} dv d\theta \quad (32)$$

where

$$n(r, \alpha) = 2R \cos \alpha \quad (33)$$

so the PDF of T_3 is:

$$f_3(t) = \frac{\partial F_3(t)}{\partial t} \quad (34)$$

So the CDF of the three hop path duration time $T^{[3]}$ can be expressed as:

$$F_t^{[3]}(t) = 1 - (1 - F_t^{[2]}(t)) \times (1 - F_3(t)) \quad (35)$$

The PDF is:

$$f_t^{[3]}(t) = f_3(t)(1 - F_t^{[2]}(t)) + f_t^{[2]}(t)(1 - F_3(t)) \quad (36)$$

The expectation of three-hop path duration time is:

$$\bar{E}_t^{[3]}(t) = \int f_t^{[3]}(t) t dt \quad (37)$$

Hence $E^{[3]}$ can be got similarly with $E^{[2]}$. Usually the path hop counts are limited by the number of the stationary nodes. The more stationary nodes, the less hop counts. In addition, the path availability will be dramatically decreased when the hop counts increased in convergecast scenario. In our experiment, we only consider path consisting at most three hops.

IV. SIMULATION AND VERIFICATION

In order to verify the correctness of our model, we compare the results of our theoretical model described above with the actual simulation results, using Qualnet[19]. The simulation terrain is a two-dimensional space(3000,3000), which represents a square area of 3000m \times 3000m. In our simulation, there is one stationary central sink having Ethernet connections with M static data sources and N mobile nodes move around with random way point mobility model (we set the pause time is 0 to match the random walk mobility model used in this paper). Both mobile and stationary nodes are equipped with 802.11 interfaces. Each mobile node periodically sends data to the central sink, via any of the stationary nodes directly or through possible relay nodes, according to its position. Due to high availability of the Ethernet connection, we only focus on the M stationary sources and N mobile nodes, which is the exact same scenario we assumed in our theoretical model. In Qualnet, we modified the built-in AODV routing protocol so that the path duration time can be obtained by calculating the life time of routing entries in mobile nodes. The average value will be calculated on all mobile nodes. M stationary nodes and N mobile nodes are randomly deployed in this area. The number of the mobile nodes N scales from 4 to 40, and the number of stationary nodes M is from 2 to 12, depending

on the simulation scenario. The magnitude of velocity is uniformly distributed in [10m/s,20m/s] and [1m/s,11m/s], and the direction is uniformly distributed in $[0,2\pi]$. In Qualnet, the value of a random variable only depends on the seed number. The result projected are an average of 25 explicit runs of simulator with 25 different seed values. The transmission range of all nodes is 400m. We use CBR application protocol to simulate the data collection process: each packet is 500 bytes long and one packet per second. The simulation period (T_E) is 250 seconds.

A. One Hop Path Duration Time

Setting $N = 1$ implies that there is only one mobile node hence only one hop path duration time is considered. Fig. 9(a) shows that the expected time from our model is quite similar with the path duration time from the simulation. Here M (i.e. the numbers of stationary nodes) is up to 12, in which case if all stationary nodes are uniformly distributed, there is little overlap and the total coverage area will be almost the same as the whole experiment area. In other words, with any more stationary nodes, the whole experiment area is fully covered; Hence no matter where the mobile node is, it can always be connected with a static source node, which is meaningless in this experiments. In Fig. 9(a) $N = 1$ (i.e. the number of mobile node is 1) and the X-axis is the number of the stationary nodes (M) and Y-axis is the path duration time. We use two different velocity distribution ranges([10, 20], [1, 11]) and the mean error rates between the model value and the experiment value are 9% and 7%, respectively. The reason is in Qualnet, the transmission range is not an exact circle, instead it uses a physical model, which means a node can send radio frame successfully as long as the signal strength sensed by the destination exceeds the threshold, to simulate wireless communication. The results also demonstrate that node with higher velocity will have shorter path duration time. In other words, dynamicity will incur poor connectivity.

B. Two-Hop Path Duration Time

We next explore a 2-hop path connection; this implies N is at least 2. A speed range [10,20] is used in our two-hop and three-hop test cases. Note in this set of simulation we only consider M up to 6, where dominated area encompasses the two-hop coverage area (i.e. $M = 7$ will cause two-hop coverage area overlap). Note that as M decreases, the dominated area is larger which implies that a larger number of hops can be accommodated within one dominated area. In this set of experiments, we choose $M \geq 4$ to ensure that we only consider one and two-hop paths. We also study the two-hop scenario with another approach that is often used in MANETs[12], [15], we call this Independent Path Duration (IPD) model. Here each hop durations are modeled as independent random variables. Results in Fig. 9(b),9(c),9(d) show that the simulation results are quite consistent with the model results, the average error rate is around 5%. Our model outperformed the IPD model in terms of accuracy, where the error rate is about to 20%. An interesting observation from the results is that when $M = 4$ and $M = 5$, if the number of the mobile nodes exceed a threshold, say $N = 30$, the

duration time from the simulation becomes higher than the one from our model. This is mainly because when N becomes larger, the opportunity that a node has a multiple-hop (more than two) path increases, especially when it is out of the two-hop coverage area (the circle with radius of $2R$). Because we do not take the multiple(more than two) hops path into consideration when $M > 4$, the duration time calculated by our model is less than the simulated one. The multiple-hop path opportunity indeed exists, but it is very small as we argued above. The situation changes when $M = 6$; the mobile nodes are almost covered by the two-hop coverage area. In this case there is less chance that a node finds a multiple-hop (more than two) path. However, according to simulation results, more stationary nodes will incur more handover, hence incur less path duration time, that is why the results derived from our model are slightly bigger than the simulated one in Fig.9(d).

C. Three-Hop Path Duration Time

We further decreased the number of stationary nodes (M) to 2. Under this scenario, the dominated area is slightly larger than the circle with radius of $3R$ and possible three-hop paths are considered. As described in III-C, the duration time of three-hop path depends on first two-hop links. We argue that although there may be four/five-hop path existing in $3R$ circle, its probability is extremely low and hence can be negligible. Fig. 9(e) shows the results of the path duration time with maximum hop number of three. The average error rate is below 10%. The main reason here is in our model, we assume that the three-hop path can only be established when the third node falls in the ring area whose radius is between $[2R, 3R]$. In fact if a node falls into the ring of $[R, 2R]$, it can also have the opportunity of establishing a three-hop path, which is hard to model. The IPD based approach needs more complicated and accurate computation in three-hop case, and we can reasonably infer its inferiority according to results in two-hop case. Hence its quantitative value is omitted here.

D. End to End Delay and the Duration Time

Two aspects are considered when establishing a relation between end-to-end delay and the path duration: a). In the ideal case, whenever the application on a mobile device sends data, there is always an available path already established by the routing layer towards the sink. However, the mobile device usually needs to wait to send application data before the path is established, which will incur delays. b). Since handover needs time, more stable links are preferred. For example, two different paths with duration time 5s each will incur bigger delays than a single path with duration time 10s, due to the handover. So the less dynamic the paths are, smaller delays will be achieved. Fig. 10 shows our results revealing the correlation between delay and the path duration time in convergecast network. The number of mobile nodes is scaled from 4 to 40. We tested three scenarios with different number of stationary nodes ($M = 4, 5, 6$). As discussed above, more stationary nodes will provide large coverage area and network access opportunities. The results show that the path duration time of $M = 6$ is longer than $M = 5$ and $M = 4$, and

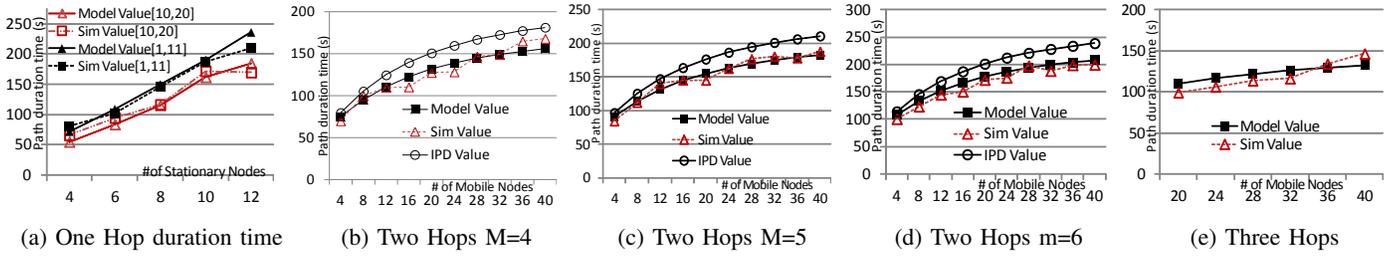


Fig. 9. Simulation results

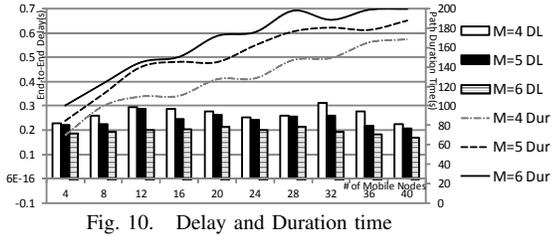


Fig. 10. Delay and Duration time

hence leads to smallest delay. With increase in the number of mobile nodes, we find the path duration time also increased. However, the distribution of end to end delay is bimodal. With increase in the number of mobile nodes, the delay first increases from $N = 4$ to $N = 12$ and then decreases, and the second local maximum point is reached around $N = 32$. The reason is that when the scale of the network is small, the path duration time is quite short. With more mobile nodes added, one needs to spend more time on handover and the newly obtained path availability can not compensate the handover time consumption. So the end to end delay increases. If mobile nodes continue being added, there are more network access opportunities that the handover time can be compensated. Thus the delay decreases. As the network scales to some extent, traffic congestion occurs, this in turn increases data transmission time. As we can observe, the delay increases again around $N = 32$. After that the enhanced path availability again dominates the end to end delay. As shown in Fig. 10 the delay decreases when $N > 32$. From the experiments, one inference is that adding more devices either stationary or mobile can improve the link availability in the network while only adding stationary nodes can continuously decrease the delay. This makes sense since the stationary nodes provide the first hop connections which are more stable. In reality, the network administrators usually deploy more stationary routers and access points to improve delay. On the other hand, carefully planning the scale of mobile nodes can also improve the end to end delay, which requires a more comprehensive understanding of delay, congestion and link availability. We will investigate that in the future.

V. CONCLUSION

In this paper, we proposed a novel path duration time model for data collection in convergecast network. We claim that the probability of the multi-hop path duration time is not merely a product of each link, instead, the n -hop path duration time always based on its previous $n - 1$ hop path. Besides, we show that how network density affects the path duration time. The results demonstrate that our model can accurately reflect the path duration time in simulation. We

also give the analysis on the correlations between end-to-end delay and the path duration time, which will help to understand the relationship between delay, path duration time and nodes density in convergecast network. This work can be further extended to employ multiple access technologies with varying network properties and transmission characteristics in future pervasive sensing network.

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