D2D Opportunistic Local Content Dissemination Sans Location Sharing

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***Abstract*—In this work, we consider the problem of local content dissemination among mobile users via decentralized device-to-device (D2D) communication, where the concerned contents have relevance only within a geographic span centered at their respective location of creation. This has several potential applications, for example, advertising and sharing contents specific to an event. To this end, we propose a scheme for locality-bounded content and information dissemination (LUCID) leveraging opportunistic D2D communications. Unlike other existing works, LUCID innovates by *not* requiring users to share locations of the centers of localities and, thereby, provides a natural defense against possible location privacy attacks. In this work, we theoretically characterize the behavior of LUCID for different locality sizes. Moreover, we investigate the extent to which an individual user can attempt to infer the location of a center of a locality, and discuss why that is difficult to achieve. Finally, we also consider an alternative version of LUCID where locations are partially shared. Results of simulation-based performance evaluation indicate that, when compared to an optimal scheme, LUCID can deliver contents to about $(\frac{2}{3})^{rd}$ of the relevant users without requiring any location sharing.**

***Index Terms*—Content sharing, Opportunistic mobile networks, Message replication, Locality, Location privacy, D2D communication**

I. INTRODUCTION

One of the promising aspects of 5G networks [1]–[4] is the availability of device-to-device (D2D) communication [5]–[7], wherein two devices can communicate directly between themselves with or without involving control links to the base station [1]. Decentralized and multi-hop D2D communication, however, is the norm in Opportunistic Mobile Networks (OMNs) [8]–[12], where nodes typically lack in end-to-end paths and exhibit intermittent connectivity among themselves. Unlike traditional networks, messages in OMNs are typically *replicated* [13]–[15] to several nodes – rather than forwarding the only copy – to improve the chances of delivery.

A particular use case of D2D communication is local content sharing (which we also refer to as dissemination or distribution) [16], [17], where relevant content is distributed to users within a given geographic locality. In this case, contents have relevance only within a geographic span centered at their respective location of creation. This has several potential applications[1], e.g., advertising and sharing contents specific to an event [16]. Fig. 1 illustrates such a scenario.

In Fig. 1, let X be an *adversary*. Therefore, if the shared content contains the value (x, y) in its header, then X can potentially misuse it. This motivates the problem addressed in this work – *how to disseminate/share/distribute a local content to relevant users without revealing the center (x, y) of the corresponding locality.* To this end, we propose a scheme for locality-bounded content and information dissemination (LUCID) that leverages opportunistic communication among the devices. It may be noted that in contrast to the scenarios with non-spatial restrictions, locality-bounded content dissemination is challenging due to the lack of any supporting infrastructure. Moreover, unlike the existing works, LUCID is challenging because of the aforementioned constraint of *not* sharing the location of origin of a message (i.e., center of the locality) with the other nodes in the network. Consequently, LUCID probabilistically replicates contents to users, where the probability of replication decreases with distance from the *perceived* location of origin of the message. By doing so, LUCID provides a preliminary defense from location privacy attacks, where a recipient of a message would be unable to identify the precise location of origin of the message and, therefore, the node that created it. This, in turn, disallows associating a user with a given location based on such a received content.

In this context it may be noted that conventional wireless broadcasting alone is *insufficient* to address the problem of local content dissemination due to two reasons. First, broadcasting has limited range and, therefore, *limited spatial coverage*. In other words, only the users located up to a certain distance can receive such broadcasted content. Second, other nodes must be *within the vicinity* of the node that creates a message at the very instant of broadcasting in order to receive the message. Moreover, the source node that created a given content item may itself move away from the region. The well-studied aspect of *opportunistic communication* in OMNs together with the store-carry-and-forward [18], [19] paradigm of message delivery, however, can help mitigate these issues.

The specific *contributions* of this work are as follows. 1) Proposing LUCID, a scheme for distributing contents to the users located within a given region without sharing the coor-

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[1] E.g., consider a person delivering a seminar who also wants to share the presentation slides with the attendees. As an another example, let us consider the scenario where a shopping mall announces a 10% discount on purchases valid for the next one hour. In both the cases, the content/information generated has (more) relevance to the users who are (or will be) in the vicinity of the event location during the specified time window.

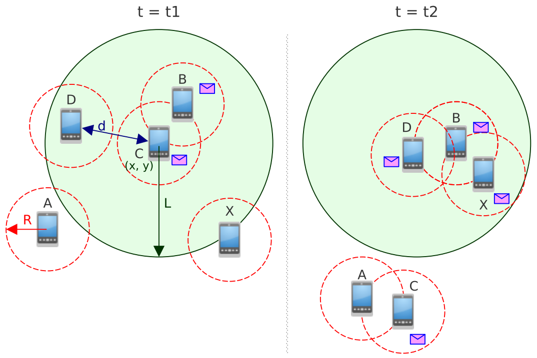

Fig. 1: Node C located at (x, y) creates a local content that is relevant inside the area with radius of locality L, and replicates it to node B at time instant t_1. Although the distance d between C and D is less than L, D does not receive the content because it is outside the communication range R. At time instant t_2, C is no more inside the locality, but B still is. Here, B replicates the content to D and X. However, A does not receive the content from C because the former is outside the concerned geographic locality.

dinates of the center of the region by leveraging opportunistic communication among the devices. 2) Presenting LUCID-S, an alternative version of LUCID, where locations of localities are probabilistically shared by the source nodes to reduce the number of users receiving contents outside a concerned locality. 3) Showing that LUCID is practically invulnerable to attempts of identifying the centers of localities by any independent adversary.

The remainder of this work is organized as follows. Section II presents an overview of locality-based content sharing schemes and privacy aspects. Section III discusses an optimal scheme for local content dissemination. Section IV presents a detailed overview of LUCID and LUCID-S. Section V briefly presents characteristics of LUCID, and explores its vulnerability toward location identification. In Section VI, we discuss about the experimental set up used to evaluate the performance of LUCID; corresponding results are discussed in Section VII. Finally, Section VIII concludes this work.

II. RELATED WORK

A. Content Dissemination

Different schemes for D2D content dissemination – both for OMNs [20], [21] as well as traditional networks [22]–[25] – are proposed, but only a few of them address the problem of distributing contents to users located within a given spatial region and typically within a given time window. Liu et al. [26] considered the use of D2D communication for traffic offloading that can help achieve load balancing in long term evolution (LTE) networks. Liu et al. [27] studied the outage probability in D2D communication with multiple devices, and observed that increasing the number of channels may adversely affect the same. On the other hand, interference is common to different kinds of communication including D2D. Sun et al. [28] used stochastic geometry-based interferer placement to analyze body sensor networks. In the context of user-centric participatory sensing, Tham and Sun [29] leveraged spatio-temporal relevance among users to offer appropriate incentive with the goal of reaching market equilibrium.

Ott et al. [16] proposed Floating Content (FC), which aims to make content “float” (remain available for certain time) in a relevant spatially-confined area. In particular, an anchor zone with two radii, a and r, is defined centered at the location of content creation by any user. Radius r defines the replication range inside which any node carrying the concerned message replicates to any other node. On the other hand, the radius $a \geq r$ defines the availability range, wherein messages are replicated to other nodes with decreasing probability that becomes zero at a distance a from the center of the anchor zone. Message replications using FC, however, requires sharing of the parameters r, a, and center of an anchor zone with other nodes, which lead to the risk of privacy leaks where users' location information can be potentially misused. Thompson et al. [17] proposed Locus, which also uses a replication function to maintain availability of content in a given locality. However, Locus, too, involves explicit sharing of location information among the users. In the context of mobile ad hoc networks, Dolev et al. [30] considered the R-LocalCast scheme and its variations, where a message sent by a node is received by other nodes within a radius R. Dolev et al. noted that R-LocalCast offers reliable delivery. However, such reliability is difficult to guarantee in the context of opportunistic communications. In fact, a scheme for local content distribution may not require for such provisioning for reliability.

B. Privacy Aspects

Dunbar et al. [31] considered the aspects of privacy in terms of distance and direction in vehicular delay tolerant networks. On the other hand, Qu et al. [32] developed a system to ensure privacy of users in the context of video data containing human face(s). In both these works, locations of vehicles were typically shared with others. Niu et al. [33] considered data caching to minimize privacy leaks. However, the proposed scheme considers a query-based system, which is unlike the proactive dissemination scheme considered in this work. Liu and Sun [34] studied various forms of attacks (e.g., against data integrity, authenticity, and privacy) and their corresponding countermeasures in the context of people-centric Internet of Things. Roth et al. [35] showed that the LTE signaling plane suffers from location privacy risks that can be exploited via the timing advance signaling parameter.

Beresford and Stajano [36] noted that the objective of location privacy is to shield one's (present or past) location information from the purview of others. In many scenarios, users would not like to have their “evidence of a visit” [36] to one or more places known by others because location privacy breaches – association of location with users – can result in compromise of anonymity[2] as well as criminal activities[3].

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[2] http://www.wmur.com/Police-Thieves-Robbed-Homes-Based-On-Facebook-Social-Media-Sites/11861116

[3] http://www.ocregister.com/articles/police-705443-fullerton-galvan.html

To understand why this is of concern in the context of local content dissemination, note that whenever a user creates a message, the address of his/her device is contained in the message's header/metadata. Such device identification information can in turn help to identify its owner. Pang et al. [37] showed that even in the absence of any device identification information, "implicit identifiers" that characterize IEEE 802.11 traffic can help in identifying the users. In particular, Pang et al. identified about 64% of the users with very high accuracy using their 802.11 fingerprinting scheme. Thus, when the source of a message and the location of its origin is known, an adversary can potentially fuse together such information to draw inferences about the user's preferences and/or habits.

To summarize, we find that although content distribution in the context of opportunistic as well as D2D communications has been studied, a rather important use case in this context, local content dissemination, has received relatively less attention. A direct approach to such locality-bounded content dissemination, which has been adapted by FC and Locus, is to share the locations with others. However, the aforementioned discussion suggests that such unrestricted sharing of locations can be prone to misuse. This motivates us to consider the problem of local content dissemination sans location sharing.

III. OPTIMAL LOCAL CONTENT SHARING

A. System Model and Assumptions

Let N be the set of nodes in an OMN formed by mobile devices carried by users. These are equipped with Bluetooth/Wi-Fi interfaces with transmission range R (see Fig. 1). Any node (user) can create a message (content) at any instant of time and intends to disseminate the message to other users in its vicinity. Since contacts in OMNs are rare and short-lived, each node is equipped with a buffer where messages are stored typically for a long time. Let M be the set of all such locality-bounded messages (contents) created in the OMN. Each message created has a finite time-to-live (TTL) value beyond whose expiry, a message expires, can be dropped.

The local content dissemination scheme depicted in Fig. 1 works as follows. Let us consider that a node, say $x \in N$, carrying a message $m \in M$ comes in contact with another node y, which does not have m in its buffer. Node x *determines*[4] whether y is inside the concerned locality of message m at that time instant. In case it is, node x transmits a copy of m to y; the hop count of m at y increases by 1. It may so happen that x moves outside the concerned locality. However, all recipients of m have a notion of the center of the locality – the coordinates where m was created. Consequently, at any later instant of time, if x comes in contact with another node z that does not have m, and x determines that z is inside the concerned locality at that moment, then x transmits a copy of m to z as well. This also allows the source node of the message (content creator) to possibly move outside the content's locality after it has replicated the message to other candidate nodes (node C in Fig. 1 at time instant t_2).

We assume that the nodes are aware of their contemporary locations (e.g., via GPS), but do not share them with one another. We also assume that no node – normal or adversary – alters the value of L contained in message headers. We also assume that any recipient can identify the source of a message (who created it) either based on message headers or some fingerprinting [37] technique. Moreover, if an adversary attempts to possibly identify the location of origin of a message, we assume him/her to do so alone and independently without any collusion. Finally, to gain insights about the performance at a high level, we ignore the link and physical layer aspects of the protocol stack, such as fading and interference.

B. An Optimal Scheme

We now discuss an optimal scheme (OPT) for disseminating local content. In particular, when a node (user) creates a message, it embeds the location of the origin (center) of its locality as well as the radius L identifying the locality within the message. Subsequently, when a node comes in contact with another node, a message is replicated only if the former is within its locality. We call this scheme "optimal" because, by using location information of the centers of localities and contemporary positions of nodes, OPT maximizes the number of users to whom a given content is reached inside corresponding localities. At the same time, it minimizes the delivery of content to users outside those localities.

Although the above scheme is simple, it involves sharing of location coordinates among the users. In this respect, OPT is similar to FC and LOCUS. However, as stated in the following Theorem, the performance of FC – measured in terms of number of users receiving content – is upper bounded by OPT.

Theorem 1: The performance of FC with replication range r and availability range a does not exceed that of OPT with locality radius L when $r \leq a \leq L$.

Proof: Let us consider a locality of radius L centered at C, as shown in Fig. 2. Let us also divide the locality into the white circular region with radius r and the gray annular region formed by the radii r and a. Contents are replicated deterministically inside the circular region, whereas probabilistically within the annular region. In particular, we assume that $a = L$. Furthermore, we assume that a user(s) with the concerned content is located at C.

At any instant of time t, let $n_r(t)$ and $n_a(t)$, respectively, be the number of users inside the circular and annular regions. Moreover, let p be the probability with which FC replicates messages beyond the replication range up to the availability range. Then, the number of users inside the locality who receives the concerned message when OPT is used is simply $n_r(t) + n_a(t)$. However, in the case of FC, it becomes $n_r(t) + p \times n_a(t)$. The difference between OPT and FC at time t becomes, $\Delta(t) = (1-p) \times n_a(t) \geq 0$. ∎

Since content replication policies used by Locus is almost similar to FC, the performance bound applies for Locus as well. Consequently, we shall use OPT as a benchmark to evaluate the performance of LUCID in a latter Section.

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[4] The underlying logic dictates the content dissemination scheme. In particular, LUCID uses a probabilistic function for this purpose, which we shall look at in Section IV

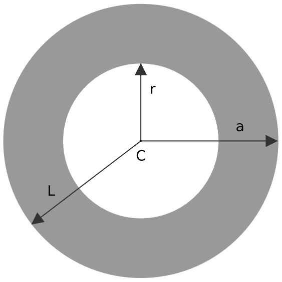

Fig. 2: Content is created at C; r and a, respectively, indicate the replication and availability radii. L is the radius of locality.

IV. OVERVIEW OF LUCID

We consider the following function for probabilistic replication of any message m.

$$\rho(m,d,L)=\begin{cases}0, & \text{if } d>L \text{ or } m.hopCount > H_{max}\\ 0.99^{d^2/L}, & \text{otherwise.}\end{cases} \tag{1}$$

Equation (1) indicates that when the distance d from the perceived center of locality (explained below) of the content is greater than L or the current hop count has crossed the maximum limit, H_{max}, the concerned content is not replicated anymore. Otherwise, the replication is probabilistic[5]. Since LUCID is unaware of the actual geographic boundary that defines a locality, the limit on hop count helps it to prevent redundant message replications across the network.

We now discuss how $\rho(m,d,L)$ from (1) is used by LUCID to disseminate contents to the relevant users by replicating messages. We recall that, in LUCID, the origin of any locality is *not* shared with others, but only the value of L is embedded within each message so that other nodes receiving it are aware of its locality bound. Nevertheless, a notion of some origin is required to compute the distance parameter d used in (1). Therefore, each node maintains a local reference point for every message carried with them.

To illustrate, let us consider a particular message (encapsulating a content), say $m \in M$, created by any node $i \in N$. When i creates the message, it locally stores (separately from the message) its contemporary location, say (x_m, y_m), against the message identifier. Subsequently, when i comes in contact with another node, say $j \in N$, the former computes the distance between (x_m, y_m) and its (i's) current location, say (x, y), so that $d=\sqrt{(x-x_m)^2+(y-y_m)^2}$. Consequently, i replicates m to the other node based on the probability $\rho(m,d,L)$ (see Algorithm 1). Here, we could allow the source node of a message to deterministically replicate it within the concerned locality. However, as Ott et al. noted [16], it could be the case that the source node is rogue and keeps on replicating over a considerably large geographic span. Therefore, we do not make such any such consideration.

When j receives the message, it does not know where m was created at. Node j, therefore, stores its *contemporary location*, say (x', y'), as the point where m "originated". Node j, in turn, probabilistically replicates m to other nodes according to the procedure described above. Here, the coordinate (x', y') is referred to as the *perceived* origin of m by j. Similarly, when another node, say k, receives m from j, the contemporary position of k becomes the perceived location of m by k; node k is unaware of either (x_m, y_m) or (x', y'). Usually, we have $(x_m, y_m) \neq (x', y')$. Replication of the message continues until its TTL expires. As a result, potential users receive the locally relevant content for the allotted time window.

Algorithm 1 shows that the time complexity of LUCID is $O(|M|)$ because it operates over at most $|M|$ elements (line number 1) with each iteration involving constant-time operation. Since the nodes require to maintain list of messages, their space complexity, too, becomes the same. The time and space complexities for the OPT scheme are $O(|M|)$ as well.

Algorithm 1: Message replication by node i to j

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Input :
  • $M_i$: Messages carried by $i$ encapsulating contents
Output:
  • Message replication decision
1 for $m \in M_i$ do
2     Compute $\rho(m,d,L)$ for $m$ using (1)
3     Generate a uniformly random number $r \in [0,1]$
4     if $r \le \rho(m,d,L)$ then
5         Replicate $m$ to $j$
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Let $d_j(m)$ be the distance from the (actual) origin of message m at which m was received by node j. Then, the mean distance of content delivery (DCD) can be computed as $\bar{D}_L = \frac{1}{|\tilde{M}|}\sum_{(j,m)\in\tilde{M}} d_j(m)$, where $\tilde{M}$ is the set of all received message-node pairs. The following Theorem characterizes variation in DCD with respect to L.

Theorem 2: The average distance of content delivery, $\bar{D}_L$, increases as the locality radius L increases.

Proof: Let $L' > L$ and $n_L = L/\Delta L$, where L, L', and ΔL are positive integers; $0 < \Delta L < L$. Moreover, let L and L' be multiples of ΔL. Let us consider that the locality of radius L is divided into a set of concentric circles of radii $\{\Delta L, 2\Delta L, \cdots, L = n_L \Delta L\}$. For simplicity, let us also assume that a node can receive a message inside a locality only at the circumference of one of these concentric circles. Assuming uniformity condition, the probability of receiving a message inside any of these concentric circles is $1/n_L$. Then, the mean DCD becomes $\bar{D}_L = \Delta L/n_L + 2\Delta L/n_L + \cdots + n_L \Delta L/n_L = \frac{1}{n_L}\Delta L(1+2+\cdots+n_L) = \frac{1}{n_L}\Delta L \times \frac{1}{2} \times n_L(n_L-1) = (n_L-1)\Delta L/2$. Now let us consider another locality with $L' > L$ and $n_{L'} = L'/\Delta L$. Then, $\bar{D}_{L'} = (n_{L'}-1)\Delta L/2$. Since $n_{L'} > n_L$, $\bar{D}_{L'} > \bar{D}_L$. Hence, the proof. ■

Theorem 3: For large L, the normalized DCD, $\bar{D}_L/L$, is a decreasing function of L.

Proof: From Theorem 2, we have $\bar{D}_L = (n_L-1)\Delta L/2$. Let us consider that $L' = L + \Delta L > L$, so that $n_{L'} = n_L + 1$. Moreover, without loss of generality, let us assume that $n_L, n_{L'} \gg 1$, which is true when L is large and ΔL

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[5] The function $0.99^{d^2/L}$ decays smoothly toward zero, which is why it is considered in contrast to other decay functions, e.g., a linear one. Moreover, it implicitly discourages very large values of L.

is relatively much smaller than L. Then, we have $\frac{\bar{D}_L}{\bar{D}_{L'}} = \frac{(n_L-1)\Delta L/2}{(n_{L'}-1)\Delta L/2} \approx \frac{n_L}{n_{L'}} = \frac{n_L}{n_L+1} \approx 1$. Based on this, we get $\frac{\bar{D}_L/L}{\bar{D}_{L'}/L'} = \frac{L'}{L} > 1 \implies \frac{\bar{D}_{L'}}{L'} < \frac{\bar{D}_L}{L}$. Similarly, it can be shown that when $L'' = L' + \Delta L$, $\frac{\bar{D}_{L''}}{L''} < \frac{\bar{D}_{L'}}{L'}$, and so on. ∎

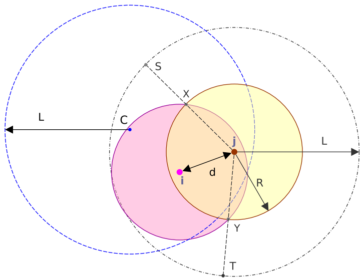
Theorem 2 signifies that as L increases, the average distance at which a node receives a message also increases. This is a necessity, otherwise, with a constant $\bar{D}$, nodes only inside an area $\pi\bar{D}^2$ would receive contents for whatsoever value of L. On the other hand, Theorem 3 implies that although DCD increases with L, the rate of increment $\bar{D}_L/L$ decreases.

In the previous sections we noted that unrestricted location sharing can have harmful effects. However, at the same time, a blanket ban on location sharing may not be very helpful. Accordingly, we consider an alternative version of LUCID named as LUCID-S, where the coordinates of the center of locality of a message is probabilistically shared by the source node. In particular, when a source node creates a message for local dissemination, it adds the coordinates of the locality into the message with a probability p_S. Therefore, any node receiving such a message knows the precise boundary of the concerned locality and computes the distance d accurately. In other words, in LUCID-S, if any node i has created a set C_i of contents, it disseminates $p_S|C_i|$ items by embedding the respective center of localities in their headers, whereas the remaining $(1-p_S)|C_i|$ items are disseminated without any such information. Note that when $p_S = 0$, LUCID-S becomes LUCID; when $p_S = 1$, LUCID-S becomes similar to OPT.

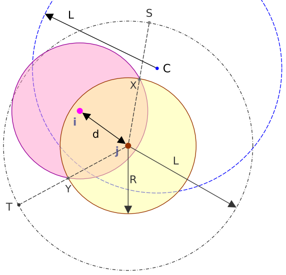
V. LOCATION IDENTIFICATION

In wireless networks, such as OMNs, where two nodes communicate when they are in their mutual proximity, risks of location identification exist to some extent even in the lack of explicit location sharing. Although the primary focus of this work is not to prevent such privacy breaches, in the following, we illustrate how such systems as well as LUCID are affected. Our objective here is to investigate the best guess that an adversary (who receives a content within its actual locality) can make about the center of the locality of any content item received. We recall that such an adversary works independently and without any collusion. Although this might not be the case for sophisticated location privacy attacks, this example would be a key to study advanced scenarios.

Let us consider two nodes, i and j, separated by a distance d, as shown in Fig. 3, where R is their transmission range. Let us assume that node i is sending a message to j. A node receiving wireless transmissions from another node knows that the other node is definitely located within a circular region of radius R. The concerned area can, however, be further narrowed down to the intersection of the transmission circles of two nodes, as depicted in Fig. 3. Let us call this area as the common transmission area (CTA). Thus, if node j somehow knows how far i is located, the former can identify the CTA. However, with omnidirectional wireless antenna, transmissions can be received from any angle so that the probability of the other user located at an angle $\alpha \pm \Delta\alpha$ (in radians) become $\frac{\Delta\alpha}{2\pi}$. The distribution of the angle is not uniform [38] in practice.



(a) Node i located between center C and node j



(b) Node j located between C and node i

Fig. 3: Transmission circles and sector construction by node j (that has received a message from i) in order to guess the center C of the concerned locality with radius L.

Furthermore, node j is aware of the locality radius L of the message received. Therefore, it can construct a circle of radius L (shown with a light-colored dotted circle in Fig. 3) around itself. The center of the concerned locality, which is the actual origin of the message, would lie inside this circle.

Theorem 4: Let us assume that node j knows[6] both α and d. Then, the center C of the locality is located inside the (minor or major) sector formed by the $\angle SjT$.

Proof: Since the angle of reception α and the distance d are known, it is possible to precisely locate node i. Consequently, the points X and Y indicating the intersections of the transmission circles of i and j can be determined. Moreover, since j nodes L, a circle of radius L can be drawn centered at it. Since the distance between C and j does not exceed L, C must lie inside this circle constructed.

Let us now join X and Y (Fig. 3) with j and extend the line segments so that they touch the circle of radius L centered at j at the points S and T, respectively. Now, as shown in Fig. 3a, if i is vertically located between C and j, the minor sector would be facing toward C. On the other hand, if j lies in between C and i, the minor sector would be facing away from C, as shown in Fig. 3b. In general, C would be located in either of the two sectors formed by $\angle SjT$. ∎

Theorem 4 presents the best guess that an adversary considered in this work can make about the center of locality of a given content. However, determining the aforementioned sectors is feasible only when both d and α are precisely known, which is somewhat difficult in reality. In addition to that, there

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[6] This can be possible to some extent, based on signal strength measurement and use of directional antenna, respectively

are two possible sectors – minor and major – formed by the concerned angle. To identify which one it is, one should know the relative locations of i, j, and C, which contradicts the original objective of locating C. We, therefore, hope that this would be enough deterrent for a not-so-sophisticated adversary to attempt in inferring the actual location.

VI. PERFORMANCE EVALUATION

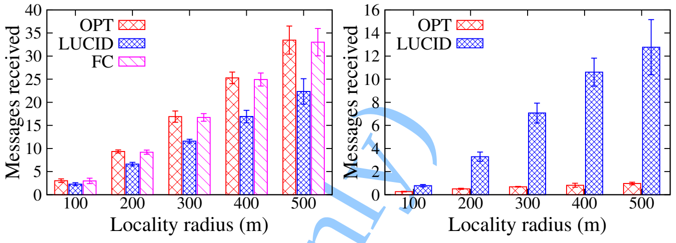
We used the Opportunistic Network Environment (ONE) [39] simulator to evaluate the performance of LUCID, and considered a synthetic mobility model based on the map of Helsinki city (4.5×3.4 sq. Km) [39] as in [16]. There were 126 nodes moving at a speed 7–10 m/s; 80 nodes representing humans moved at a speed 0.5–1.5 m/s. The remaining nodes moved at a speed 2.7–13.9 m/s. To discount any effect of limited storage capacity upon the performance, we considered the buffer size of each node to be infinite. All nodes transmitted with a speed of 250 kBps up to a range of 10 m. The nodes created messages after about every 45 minutes and their sizes were uniformly distributed between 1–50 kB.

We considered different scenarios by varying the locality radius L from 100 to 500 m while keeping the TTL fixed. Next, we varied considered different values of message TTL while keeping L fixed. Unless otherwise specified, the maximum hop count was taken as five. The simulation duration was taken as 24 hours. Each simulation scenario was repeated for 10 random seed values based on which the ensemble average and 95% confidence interval were computed. In case of FC, we considered the replication range (r) to be half of the availability range (a); the value of a was set to L (e.g., when $L = 250$ m, we took $a = 250$ m and $r = 125$ m). Note that when $r = a = L$, FC becomes OPT.

We considered the following metrics to evaluate the performance of LUCID. 1) Average number of messages received by users *inside* the concerned localities (the ratio of the number of messages received inside to the number of messages created) and 2) Average number of messages received by users *outside* the concerned localities. Note that the number of (non-unique) users receiving messages is directly proportional to these numbers because every message delivery is associated with a user. In both the cases, we considered the location of a (mobile) user when a message was successfully received to determine whether the user was "inside" or "outside" the concerned locality. Additionally, we also looked upon the DCD measures, as discussed in Theorem 2. We compared the performance of LUCID against the optimal scheme, OPT.

VII. RESULTS

Fig. 4a shows the average number of messages delivered inside the corresponding localities. It can be observed that as L increased, the number of contents delivered inside the localities also increased in case of LUCID, FC, and OPT. In general, the number of contents delivered (and therefore, the number of users reached) by LUCID was about $(\frac{2}{3})^{rd}$ of OPT. This is a significant observation – one can deliver contents to two-third potential users even without sharing actual coordinates of their localities. Moreover, the results validate the claim that OPT is optimal (Theorem 1).



(a) Inside locality (b) Outside locality

Fig. 4: Effects of locality radius L on the number of users reached.

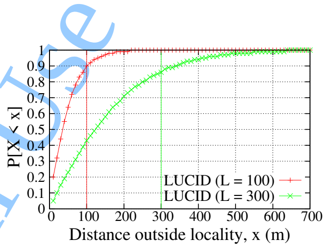


Fig. 5: CDF of content delivery outside a locality.

Fig. 4b shows the average number of messages received by users outside the corresponding localities. As noted earlier, probabilistic replications of LUCID has a side effect that some users outside the locality of a given content would receive it. However, the numbers were less than the counts shown in Fig. 4a. Moreover, it should be noted that even with OPT, the number of users receiving contents outside the localities is not zero because of nodes moving in/out of localities during message transmissions. The values obtained using FC were very close to OPT and therefore, are not shown here.

Fig. 5 shows the empirical cumulative distribution function (CDF) of distance at which contents are received outside the locality when LUCID was used. Two different localities with $L = 100$ and 300 m were considered here. The x-axis in the Fig. shows distance from the boundary of the locality, whereas the y-axis shows the fraction of messages that were delivered up to that distance. E.g., when the locality radius $L = 100$ m was considered, 90% of the messages that were delivered outside the concerned locality were received by nodes between 100 ($= 100 + 0$) m and 200 ($= 100 + 100$) m from the center of that locality. Similarly, when $L = 300$ m, about 90% of the messages delivered outside were received between 300 ($= 300 + 0$) m and 600 ($= 300 + 300$) m from the concerned locality's center. In other words, the message replications in LUCID were mostly limited up to about the distance $2L$ from the center of a locality, beyond which it steadily decreased. This might tempt to reduce the radius L to $L/2$. However, that will be counter-productive, because with halved L, the extent of replications will also decrease.

Fig. 6 shows the effect of TTL on local content dissemination when L was taken as 250 m. The Fig. clearly indicates that increase in TTL is helpful in disseminating more content to users. In the Fig., plots with legend "LUCID (inside)" indicate the average number of messages delivered by LUCID inside

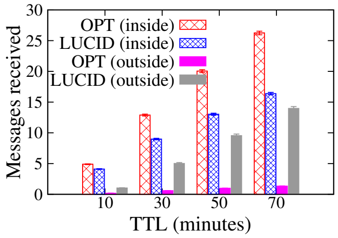


Fig. 6: Effects of TTL on local content sharing.

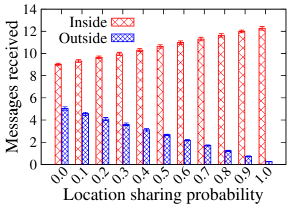


Fig. 7: Effects of p_S on content dissemination using LUCID-S ($L = 250$ m).

the concerned localities. On the other hand, those labeled with "LUCID (outside)" indicate the average number of messages disseminated to outsiders by LUCID. However, it can be observed that the difference between OPT and LUCID grew wider as TTL increased. Thus, the trends from Figs. 4a and 6 roughly indicate that when no location is shared, LUCID fares best with smaller TTLs and not-so-big localities.

Fig. 7 shows the effects of location sharing probability (p_S) upon local content dissemination when LUCID-S was used. It can be observed that as p_S increased, the average number of contents received by users inside the corresponding localities also increased. At the same time, the number of users receiving such contents outside the localities steadily decreased. It may be noted that when location of the center of localities were always shared ($p_S = 1$), LUCID-S disseminated contents to 12.33 users, on an average, in contrast to 12.91 users reached by OPT. Moreover, in this particular scenario, about 36% more relevant users received contents by always sharing locations compared to by never sharing locations.

Fig. 8 shows the effects of variation in locality radius L on the average and normalized DCD. In particular, as L increased, the mean DCD (shown using bar plot) also increased. However, the normalized DCD (shown using line plot) increased initially, but decreased later as L became large. When L was 400 m, the value of the normalized DCD was found to be about 0.9. A value close to unity indicates that most users, on an average, received contents inside their respective localities.

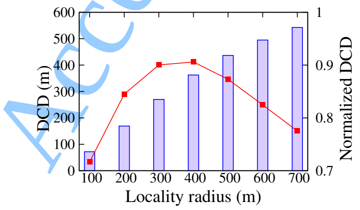


Fig. 8: Variation in DCD with locality radius L.

Due to the very nature of the message replication function in (1), we expect the value of normalized DCD to fall below unity when L is further increased. The results from Fig. 8 also validates the claims made in Theorems 2 and 3.

Fig. 9 shows the effect of H_{max} upon the performance of LUCID. As the upper limit on hop count of messages increased, the extent of message replication in LUCID also increased. Consequently, more users within the concerned regions received the contents. However, the higher rate of replication also caused more users outside the region to receive the contents as well. The Fig. shows that the gap between inside and outside recipients became narrow at $H_{max} = 5$. Consequently, a value of $H_{max} > 5$ may not be useful.

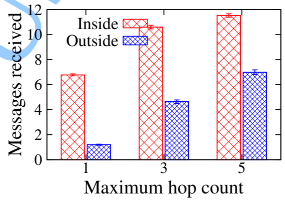


Fig. 9: Effect of maximum hop count (H_{max}) upon LUCID.

VIII. CONCLUSION

In this work, we proposed LUCID for disseminating locally relevant contents. The problem is challenging since, unlike existing works, LUCID does not require sharing of locations of the origins of localities and thereby, reduces the chances of location privacy attacks. However, at the same time, a blanket ban on location sharing may not be always relevant or necessary in real-life. Consequently, we proposed LUCID-S, a variant of LUCID, where the source node probabilistically shares the coordinates of the concerned localities. In the future, this work can be extended in several ways, e.g., by taking into account trust, rate control, and dissemination priorities.

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