On the Undecidability of Mobility Prediction and What to Look at in Mobility to Improve Communication in Mobile Networks

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***Abstract*—This work presents an analysis of mobility prediction, concluding that it is an undecidable problem. Even though one cannot always predict even its own future movement actions, it does not mean that there is no use for mobility knowledge. In mobile networks, better knowledge on how and when a node (hereafter referred as a *mover*) will decide on its next movement actions might lead to near-optimum protocol performance. In such situations, before endeavoring into sophisticated analysis by way of restricted mobility traces gathered just for that purpose, one could start checking on how much we already know (or are able to find out) about mover's actions. Based on that, the next step would be to work on how to use mobility data more appropriately. As we use such data, we can increasingly better understand mobility, making space for adaptive communication protocols. Such methodology does not go against any other analytical studies for capturing mobility properties; on the contrary, it just anticipates other uses for mobility data. Even though it is not feasible yet to consider upgrading existing routing protocols, so that full mobility knowledge is taken into account, one can envision an application routing over an overlay network. There is much hope for such an approach given that mobile networks are going to be more widely available as the Internet-of-Things evolves.**

***Keywords*–Mobile networks; mobility metrics; communication protocols; computability; undecidability.**

I. Introduction

It would be interesting to devise an algorithm for computing all future paths to be taken by a mobile node (hereafter referred to as a *mover*). Understanding mobility at such level would provide means for solving many problems in real life, including networking by way of optimum communication protocols in mobile ad hoc networks (MANETs) [1]. Nevertheless, is it really possible to construct such algorithm?

One could start by comparing such an endeavor to other similar problems already addressed in computer science. Lloyd [2] proposed a turing test for free will, which consists of determining whether one (or any other external decider) can know one's decision before the decision is even taken. He concludes that, regardless if the world is deterministic or not, the one who passes the test is inclined to believe that he is endowed with free will, because it is an undecidable problem.

A mover can be anything capable of wandering around under a given scenario, considering all its constraints, which can be as complex as we can imagine. However, one could imply that mover's actions follow some pattern, which could possibly be identified if there would be enough data on mobility traces for analysis. Such an approach has already been taken for some specific mobility targets (*e.g.*, human mobility [3] [4]). Nevertheless, the results usually provide just some probabilistic insights into mobility patterns, which are specially useful for enhancing mobility aware protocols.

A path can be thought of as a sequence of actions taken by the mover when going from point `A` to point `B`, and it is up to the mover to choose the next action. As for the whole path, one can ask if the mover is able to predict *all* future actions it will take. Of course, if the mover has the capabilities to do so, we have already answered the very first question.

What we take into account in terms of computer capabilities could also be decisive to solve this problem. Assuming that quantum computers can efficiently simulate the laws of physics, it is also possible to conceive quantum Turing machines [5]. The inner process involved in every mover's action can be thought of as a sequence of operations. The situation is such that whether the mover itself or any other mover tries to simulate such sequence of operations, it will take more time than the original mover's sequence of operations [2].

Once assured on the undecidability of mobility prediction, one should not give up on finding ways to somehow explore mobility information whenever available. This leads to laying out the underlying requirements for taking part in the network or the services' agreement the mover has agreed upon. Based on the mobility information the mover is going to make available, the next step is to identify services/protocols, which can take advantage of such information. One desirable approach would be having the basic networking services working with and without mobility information. That is, mobility knowledge should be used to improve existing networking services, basically following an on demand and software defined network approach [6] [7].

Therefore, before starting gathering mobility traces for sophisticated analytical analysis, it is worth checking what mobility data can be assumed as granted in given scenarios. It does not mean that such analytical studies are not worth the effort, but one might ask if the desired services are not achievable through simpler approaches employing information and mechanisms known to be available beforehand. In addition, getting mobility traces might end up being impractical or not so representative depending on the sampling methodology or the number of participants.

As the network evolves, mobility traces could also be stored for later processing. That is, as there will be more mobility traces over time, it will be possible to go further into the

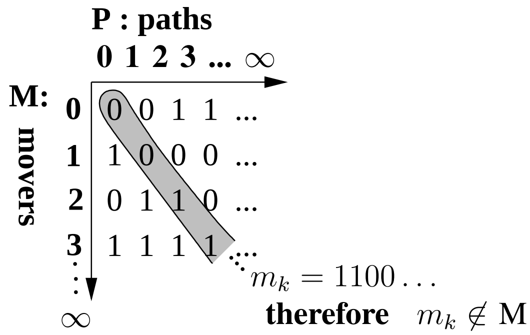

Figure 1. Cantor's diagonal argument applied to the mobility prediction problem.

analytical analysis as well (as a desirable *side effect*). In this case, mobility metrics can be employed to better capture some mobility properties [8].

Briefly, the remainder of the paper is organized as follows. In Section II, we start by showing that mobility prediction is an undecidable problem. That is, there is no way to know in advance what is the path to be taken, or not, by any mover (not even by the mover itself) in *all* situations. In Sections III and IV, we focus on how mobility awareness could improve communication in mobile networks. In Section IV, we conclude this work.

II. The Undecidability of Mobility Prediction and its Implications

Let us consider two countably infinite sets, one for all the movers,

$$M = \{m_0,\ m_1,\ \dots\ m_i,\ \dots\ \},$$

and the other for all the paths,

$$P = \{p_0,\ p_1,\ \dots\ p_j,\ \dots\ \}.$$

We are going to leverage our analysis on Cantor's diagonal argument [9], showing that it is not possible to devise an algorithm for computing whether a mover will or will not take a path *for all pairs* (m_i, p_j).

For that, we start by taking into account the Cartesian product $M \times P$ as the domain set of a function f, where every pair (m_i, p_j) is mapped to 1 or 0, showing, respectively, whether mover m_i will or will not take path p_j (see Figure 1). Therefore, each row represents the possible movement actions (*i.e.*, paths) of a mover; that is, each mover in M is represented as an infinite binary sequence.

If we can show that there is a mover, m_k, which is not present in the set of movers, we actually show that the set M is uncountably infinite. To devise such mover, for each i-th position of the sequence describing m_k we assign the complement of $f(m_i, p_i)$. By doing so, mover m_k's sequence differs by one position from every single mover in the set M and, therefore, $m_k \notin M$. This is a contradiction, because we had assumed that all movers were included in the set M.

As the number of Turing-recognizable languages (*i.e.*, decidable sets) is countable [9], there is no algorithm capable to deal with an uncountably infinite set of movers. Thus, for all possible movers and paths, it is not possible to know beforehand whether a mover will take a particular path or not. Therefore, mobility prediction is an undecidable problem.

When employing recursive reasoning, one uses a mathematical relationship between terms in a given sequence, and such recursive computation can be simulated by either classical or quantum Turing machines [5]. If any system must operate according to the known laws of physics, meaning that the world itself could be simulated by a Turing machine, one can conclude that:

1) There is no general technique to determine whether or not the mover is going to follow a given path at all (*i.e.*, the Cantor's diagonal argument).
2) In case the mover is under a time constraint, then trying to determine the movers next path sometimes takes more time than the mover takes to perform the actions.
3) A computationally universal mover can not answer all questions about its future behavior.
4) A time constrained computationally universal mover takes more time to simulate its next path than it takes it to actually perform that process directly.

Lloyd [2] employed the same reasoning for showing that one cannot prove that a decider does not possess free will; however, one cannot prove that one has free will either. Basically, one can always claim its decision as one's own choice, and behave as possessing free will.

With all that said, it does not mean that one cannot ever determine a given mover's next path. Nevertheless, it is also clear that one cannot *always* determine any mover's next path.

Next, we explore ways to take advantage of the mobility information which is already granted in many situations. That is, before taking on any complex analytical approach, start from the mobility information that can be **provided by the users/movers themselves**, and build around that the protocols/applications that can be used right away in mobile networks even when it is not possible to change the behavior of the lower layer protocols (*e.g.*, network protocols).

III. Mobility Awareness in Mobile Networks

In this section, we ask ourselves how mobility awareness might improve communication in mobile networks. It is always desirable to have the means and mechanisms to improve the network performance overall, but the focus here is just on the benefits from exploring mobility itself. Figure 2 presents an overall schematic and guidelines for the mobility information addressed in this section.

A. How much we know about mover's actions?

Taking into account mobility information when devising communication protocols may help improve the overall network performance; and this has already been done [10]–[12]! However, as it is not possible to predict *all* future movers' actions, one could well focus just on the information which is somehow related to mobility in an acceptable and predictable way for at least some situations (which might be exactly the ones we are interested in). In such cases, and before trying to gather real traces for sophisticated analytical analysis, it is worth focusing on the mover's mobility data known in advance to some acceptable degree of detail. To begin, one could pinpoint some important mobility information such as:

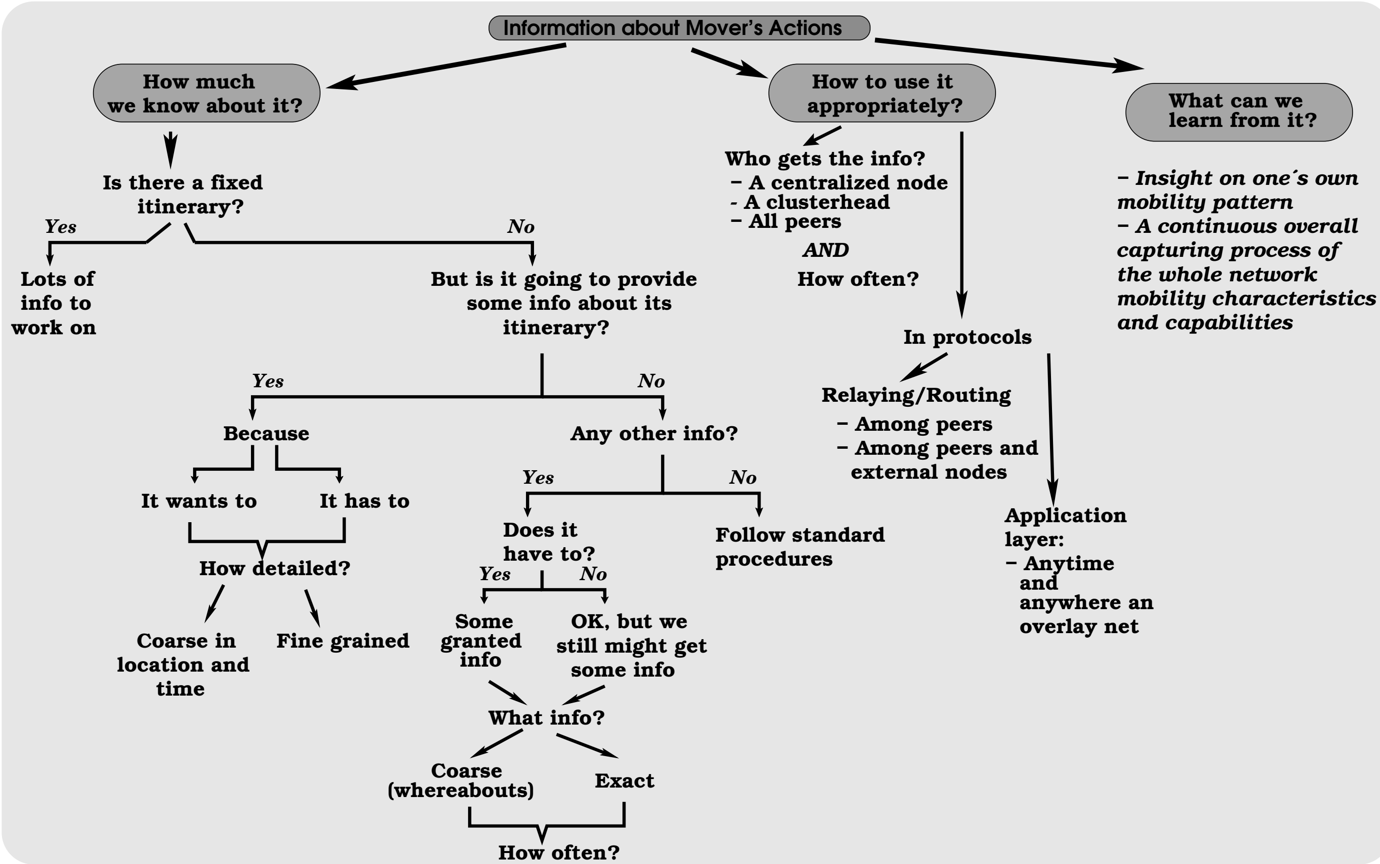

Figure 2. Overall schematic and guidelines for mobility information.

- *Is there a repeating schedule with fixed stopping points (e.g., bus terminals)?* Even though one might not know in advance all intermediary positions when a mover is going from a starting point A to a finishing point B, just having the information about where the mover should be at certain points in time is paramount if one would like to schedule a message/packet relay to well known communication agents (probably static routers) at stopping points. Note that it is not the same as not knowing when movers are expected to show up at some defined communication points (as static routers by a highway waiting for *any* mover wandering about).
- *Is the mover willing to make available its exact location or, at least, its whereabouts?* Considering there are ways to protect one's confidentiality and privacy, find ways to explore how we could enhance communication protocols given that movers are willing to help by providing some information about their location (either exact or an approximation). Even though this might sound unacceptable sometimes, the fact is that there are ways to better explore these situations specially when such information has already been made available voluntarily by users through many apps/servers (*e.g.*, Global Positioning System (GPS) location may be embedded within tweets in Twitter).
- *Must the mover provide its location periodically?* This hypothesis is stronger than the previous one, because now the mover does not get to choose if it shares its location or not. The point here is **how often** the mover does so, as well as assuming that there is a communication link at such moments (*i.e.*, it is not about recording one's position for later transmission).
- *Is the mover willing to provide some details about its itinerary?* As for the case when the mover has fixed stopping points, which are scheduled to be reached at some known points in time (with an expected variance), a mover could make available its complete itinerary. The point here is how much detail is expected to be provided by the mover (*i.e.*, *How well characterized is the itinerary?*):
  - The mover could provide both GPS coordinates and their expected reaching times;
  - Or just GPS estimates and coarse target times.
- *Must the mover provide some details about its itinerary?* Likewise, the mover might be forced to provide its itinerary as part of the communication service itself. In this case, even though there are security concerns whenever location information is shared with a third party, there are ways to guarantee privacy, confidentiality, and integrity.

B. *How to use mobility information appropriately?*

With the mobility information available, one can start focusing on when and where such data should be part of any decision making process. Communication protocols must comply with safety and liveness properties, while efficiently handling the available resources. Firstly, it is necessary to address the following questions:

- *Who receives mobility data information?*
  - A centralized entity;
  - A cluster/leader (cluster-head) in the vicinity;
  - Or data gets broadcasted among *all* peers.
- *How often mobility information is obtained and sent out by movers?* This will depend on the information granularity and the imposed restrictions/requirements among the entities involved in the communication.

Secondly, it is required to sort out how mobility information might be useful for communication protocols:

- For the link layer and routing, the mover itself could act as a router/relayer:
  - Among movers, whether mobility information is shared directly among movers or it comes from a centralized node or cluster-head;
  - Among movers and external nodes (*e.g.*, any node in the Internet): for example, in situations where a centralized node acts as an access point to the Internet.
- For the upper layers (*e.g.*, application):
  - Application content can be shaped according to on demand needs as we know the mover's whereabouts or its intended destination.

C. What can we learn from mobility?

As mentioned before, as a sort of *good side effect*, mobility information can be gathered for further analysis in a similar fashion as mobility traces are captured just for analytical studies. However, it is not likely to produce as many details as when it is solely planned for capturing mobility traces. Considering the situations pinpointed earlier, by default, the obtained traces are going to include some but not necessarily all positions taken by the mover.

Nevertheless, even though the mover desires to or has agreed upon providing only the required mobility information, locally it can always track its own movement with more detail for later use or to make it available to analytical analysis, if desirable. At the end, it is even possible to have more and better traces compared to those obtained just for some specific purposes.

It is even worth checking how the mover might help itself when analyzing its own movement actions. For example, if the mover has a predictable behavior for the next hours or days, it could plan where and when to get and send information in advance. In addition, if the mover shares this information with other peers or a centralized node, there will be plenty of other possibilities.

According to Tanenbaum [13], "Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway". Whatever storage capabilities one can conceive, either in terms of storage capacity, size, and data transfer rates, it is always possible to imagine that data can be stored in the movers memory and be delivered later when reaching the destination or getting closer to it (in terms of communication connectivity or geographical location).

As one learns from its own behavior and from other peers, it is possible to combine traditional communication approaches with customized ones, and they could well be implemented at the application layer as an overlay network infrastructure [14]–[16]. There are many possibilities in this case: for example, considering the movers capabilities that are acceptable for a given delivery task (*i.e.*, transporting a large backup file from its own application or from another peer to the cloud), once it is known in advance that the mover will stay connected to a fast network for enough time (*i.e.*, for relaying the content or delivering it directly to the destination), such task could well be planned accordingly.

IV. Well said, but what to do then?

So far, we have been looking at how much mobility information is available, how we could possibly use it, and how we might improve our overall knowledge on mobility for enhancing communication in mobile networks. One can take for granted that there will be an ever growing number of mobile entities with computer and communication capabilities (*e.g.*, the Internet-of-Things [17] promises to contribute to that); therefore, it is reasonable to consider a richer communication environment. In such context, it is worth to take into account a software defined network approach whenever conceiving ways to take advantage of mobility information. In this sense, it might be possible to improve communication performance in mobile networks even when focusing just on the application layer itself.

When it comes to using such mobility information, one should consider it as coming from a continuous feedback process, evolving as the network advances. Once again, it does not go against any particular mobility aware protocol approach based solely on specific captured mobility patterns; however, following our proposed methodology, one could start right away from existing communication protocols by extending them or working just on the application layer. As pointed out before, movers' current locations and the next intended ones are straightforward for applying into routing processes in mobile networks.

In a wider network environment (*e.g.*, the Internet), of course it would not be an easy task to adapt the existing routing protocols to take into account mobility data in a broader sense. However, given that we expect movers to be at the last mile of the network, an application layer routing over an overlay network [18] is possibly the most attractive alternative when it comes to employing the proposed methodology. While in direct reach of each other, movers could act as routers among themselves, and whenever relaying any message/packet, decisions should be leveraged on the better expected result in terms of who can possibly make it faster to the desired destination (or fixed infrastructure leading to the destination) based on the known mobility information. This might sound like any traditional routing approach, but the difference here is that it could be based on the mobility information provided by those who know better about it: the movers.

Let us look at an example (see Figure 3 as a reference). Consider mover **A** wants to send a backup file to a restricted private cloud infrastructure accessible only to peers taking part in the group. Having the mobility information of some of **A**'s peers (*i.e.*, movers **B**, **C**, **D**, and **E**), mover **A** decides to transfer the file to mover **B** because it is going to be closer to another

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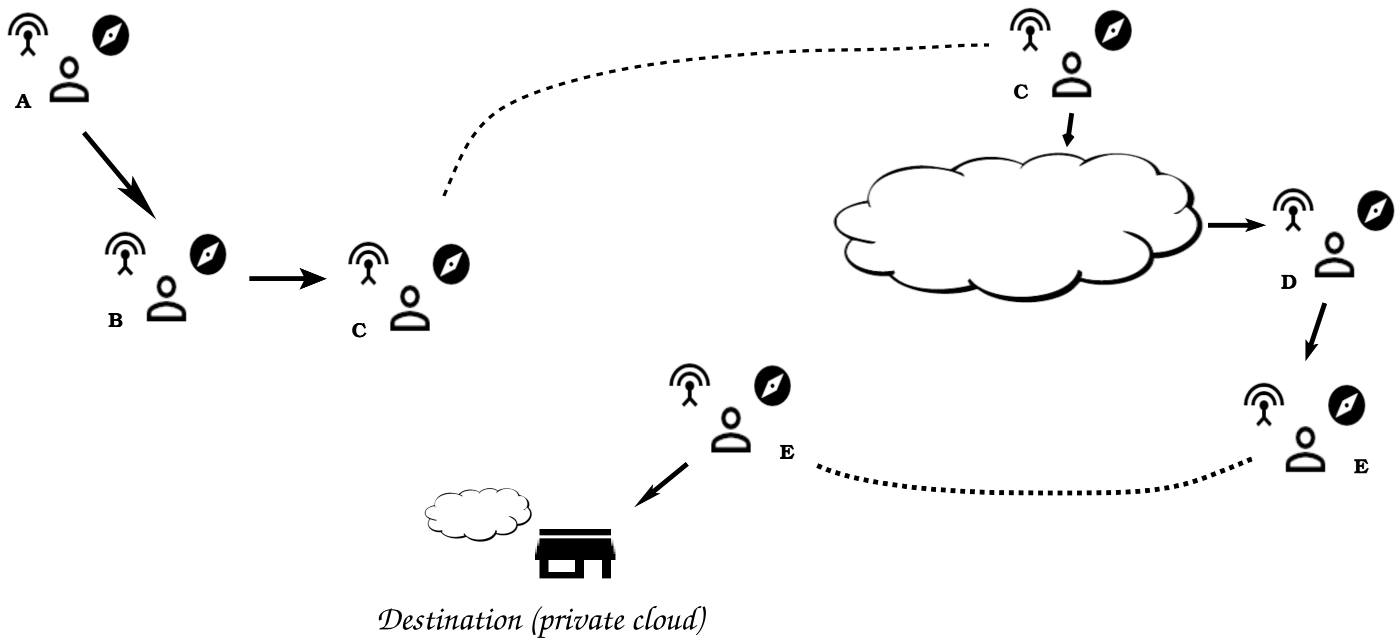

Figure 3. *What can we do then?* An example of an application routing approach based on an overlay network.

mover, **C**, for an acceptable period of time (*i.e.*, enough time for transferring the backup file). In turn, later on, mover **C** is known to shift to a place where it is going to stay connected to the Internet for some extended period of time. Besides that, it is also known that there is another peer, mover **D**, which is going to stay connected for enough time to get the backup file relayed through the Internet from mover **C**. In addition to that, mover **D** is also a good candidate because it can relay the file to another peer, mover **E**, which is known to get in touch with the destination (a private cloud infrastructure) later on.

Even though this short example might sound a little far from reality now, it is likely that such application overlay networks will become common given the infrastructure to be built on and around the Internet-of-Things.

One could as well argue that mobility awareness has been receiving plenty of attention when designing communication protocols so far [10]–[12] [19]–[21]; however, what is actually proposed here is that we could change the *starting point* when designing such protocols: first of all, analyze what useful mobility information *coming from the user/mover* is already available or otherwise could be made available, and starting to work with just that. Depending on the application requirements, and the required security protocols, we could possibly achieve better, or at least reasonable, performance results.

V. Conclusions

Even though it is impossible to predict *all* movement actions of any mover, one could possibly enhance communication considering just what one already knows about its own mobility actions, from other peers, and eventually from a centralized point of coordination.

Basically, before going through specific analytical analysis (usually based solely on a restricted set of mobility traces), we should focus on mobility information we could get spontaneously or as part of the protocol/application requirements/agreements. Again, this does not mean one cannot continuously strive to improve one's insight into mobility patterns through the analytical approach. This can also go hand in hand with the proposed methodology because mobility traces are a possible *good side effect* of collaborative mobility aware protocols/applications.

Using mobility data appropriately can improve overall mobile network performance and introduce new features and services not available yet (*e.g.*, better cloud service experience in a mobile environment) due to its intrinsic limitations. First, one must take into account who actually gets such data (*i.e.*, all peers, a centralized node, or cluster heads). Periodicity is also crucial here, because of its impact on accuracy. When thinking about protocols, depending on the granularity and accuracy of mobility data, routing can be enabled among peers or among peers and a fixed infrastructure. At the application layer, with the implementation of overlay networks, one can really expand the mobile network possibilities, and there are plenty of security mechanisms available for making it attractive even to more concerned users.

What is missing then? Essentially, when designing new mobility aware protocols, we suggest that a methodology similar to the one proposed here be followed: start from the mobility knowledge that is somehow granted given the requirements/agreements for some service. That is, one should start working on the mobility information provided by the movers themselves. It is even possible that a more sophisticated approach may end up not providing better performance results or just only marginal improvements not worth the cost. Taking into account the promises around the Internet of Things, simple solutions for mobility awareness should be strongly considered.

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