A Complex Network Analysis of Human Mobility

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Abstract—Opportunistic networks use human mobility and consequent wireless contacts between mobile devices, to disseminate data in a peer-to-peer manner. To grasp the potential and limitations of such networks, as well as to design appropriate algorithms and protocols, it is key to understand the statistics of contacts. To date, contact analysis has mainly focused on statistics such as inter-contact and contact distributions. While these pair-wise properties are important, we argue that structural properties of contacts need more thorough analysis. For example, communities of tightly connected nodes, have a great impact on the performance of opportunistic networks and the design of algorithms and protocols.

In this paper, we propose a methodology to represent a mobility scenario (i.e., measured contacts) as a weighted contact graph, where tie strength represents how long and often a pair of nodes is in contact. This allows us to analyze the structure of a scenario using tools from complex network analysis and graph theory (e.g., community detection, connectivity metrics). We consider four mobility scenarios of different origins and sizes. Across all scenarios, we find that mobility shows typical small-world characteristics (short path lengths, and high clustering coefficient). Using state-of-the-art community detection, we also find that mobility is strongly modular. However, communities are not homogenous entities. Instead, the distribution of weights and degrees within a community is similar to the global distribution of weights, implying a rather intricate intra-community structure.

To the best of our knowledge, this is the most comprehensive study of structural characteristics of wireless contacts, in terms of the number of nodes in our datasets, and the variety of metrics we consider. Finally, we discuss the primary importance of our findings for mobility modeling and especially for the design of opportunistic network solutions.

I. INTRODUCTION

The rapid proliferation of small wireless devices creates ample opportunity for novel applications [1], as well as for extending the realm of existing ones. Opportunistic or Delay Tolerant Networking (DTN) [2] is a novel networking paradigm that is envisioned to complement existing wireless technologies (cellular, WiFi) by exploiting a niche performance-cost tradeoff. Nodes harness unused bandwidth by exchanging data whenever they are within mutual wireless transmission range of each other (in contact).

Since every contact is an opportunity to forward content and bring it probabilistically closer to a destination (or a set of destinations), understanding statistical properties of contacts is vital for the design of algorithms and protocols for opportunistic networks. To this end, a number of efforts have been made to collect mobility traces at various scales using different methods [3], [4], [5], [6].

Analysis of such traces has led to several important findings: On an individual level, mobility patterns exhibit time-of-day periodicity and strong location preference [7]. The amount of regularity observed implies high (statistical) predictability of these patterns [8]. On a pairwise level, most trace analysis research has focused on inter-contact and contact duration statistics [9], [10] and it is still debatable whether these distributions are power-law, have exponential tail, or have qualitatively different behavior from on pair to another. More recently, studies have focused on the macroscopic structure of contacts such as tightly knit communities of nodes that meet each other frequently. Such community structure is generally assumed because of the social nature of human mobility. In fact, some state-of-the-art mobility models [11] explicitly model community structure, and most recent DTN routing protocols [12], [13] exploit structural characteristics. However, there are few studies that systematically measure the macroscopic structure of mobility. Notable exceptions are [12], reporting high modularity of contacts (i.e., strong community structure), [14] finding short average path length in opportunistic networks, and [15] analyzing the time-dependence of communities.

In this paper, we provide a thorough and extensive analysis of the structural properties of contacts. To do so, we represent contacts in a compact and tractable way as a weighted contact graph, where the weights (i.e., tie strengths) express how frequently and how long a pair of nodes is in contact. Given such a contact graph, we can use tools and metrics from social network analysis and graph theory (e.g., connectivity metrics, community detection, etc.) to quantify the amount of structure in the underlying mobility scenario. Our main findings and contributions can be summarized as follows:

i) Our study is based on 4 contact traces ranging in size from ~100 to ~1000 nodes, hence, we add one order of magnitude compared to prior works (which have only analyzed contact graphs of ~100 nodes). We also present a completely new trace reporting the whereabouts of users using a popular location-based smartphone application (Sec. II).

ii) We provide thorough evidence that the structure of mobility has small-world properties typically observed in social networks. While previous work [14] has only shown that there exist short space-time paths (possibly formed by random, unpredictable contacts), our methodology allows to conclude that the strong and predictable structure is small-world (Sec. III).

iii) We show that contacts are strongly modular, i.e., that there are close-knit communities of people with strong mobility ties. We study and compare the distributions of tie strengths and node degrees within and across communities. We find high
variance and heavy tails on both levels, implying that communities are by no means homogenous entities. In all traces, we find surprisingly similar distributions within communities and on a global level, suggesting that a community itself has properties similar to the entire network (Sec. IV).

iv) We discuss the implications of these findings for the design of opportunistic routing protocols and mobility modeling (Sec. V).

II. DATASETS AND CONTACT GRAPH

In this section, we detail the mobility scenarios we use in our study, and how we derive contact traces from them (II-A). Finally, we explain our methodology of creating an aggregated contact graph from such a contact trace (II-B).

A. Mobility Scenarios and Contact Definition

We define a contact as the period of time during which two devices are in mutual radio transmission range and can exchange data. For our analysis, we use four mobility traces collected in different contexts and with different methods: WLAN Access Point associations from the Dartmouth and ETH Zurich campuses, Bluetooth contacts from the MIT campus [4], and family and friend activity by intention or familiar strangers because of similarity in their mobility patterns. Our goal is to represent mobility correlation (in space and time) between two nodes. Observed contacts. This weight should represent the amount of interaction or similarity between nodes and reflect the complex structure in people’s movements: meeting strangers by chance, colleagues, friends and family by intention or familiar strangers because of similarity in their mobility patterns. Our goal is to represent the complex resulting pattern of who meets whom, how often and for how long, in a compact and tractable way. This allows us to quantify structural properties beyond pairwise statistics such as inter-contact and contact time distributions.

To represent the structure of a mobility scenario, we aggregate the entire sequence of contacts of a trace to a static, weighted contact graph \(G(N, W)\) with weight matrix \(W = \{w_{ij}\}\). Each device (or rather person carrying a device) is a node of this graph and a link weight \(w_{ij}\) represents the strength of the relationship between nodes \(i\) and \(j\). A key question is how to derive the tie strength between two nodes, i.e., what metric to use for \(w_{ij}\), based on the observed contacts. This weight should represent the amount of mobility correlation (in space and time) between two nodes. Various metrics, such as the age of last contact [16], contact frequency [12] or aggregate contact duration [12] have been used as tie strength indicators in DTN routing.

1http://gowalla.com

2With the tie strength described in Sec. II-B the chosen duration does not affect the contact graph if all contacts have the same duration.
In our study, we consider both, contact frequency and aggregate contact duration. They capture different aspects, both of which are important for opportunistic networking (e.g., for data dissemination). Frequent contacts imply many meetings and hence many forwarding opportunities (short delays) and long contacts imply meetings where a large amount of data can be transferred (high throughput)\(^3\).

Since most network analysis metrics require one-dimensional tie strengths, we map these two features to a scalar weight. We first assign each pair of nodes a two-dimensional feature vector, \(\mathbf{z}_{ij} = \left(\frac{t_{ij} - f}{\sigma_f}, \frac{t_{ij} - \bar{t}}{\sigma_t}\right)\), where \(t_{ij}\) is the number of contacts in the trace between nodes \(i\) and \(j\), and \(\bar{t}\) is the sum of the durations of all contacts between the two nodes. \(f\) and \(\bar{t}\) are the respective empirical means, and \(\sigma_f\) and \(\sigma_t\), the empirical standard deviations. We normalize the values by their standard deviations to make the scales of the two metrics comparable. We then transform the two-dimensional feature vector to a scalar feature value, using the principal component, i.e., the direction in which the feature vectors of all node pairs \(\mathbf{Z} = \{\mathbf{z}_{ij}\}, i, j \in N\) has the largest variance. This is the direction of the eigenvector \(\mathbf{v}_1\) (with the largest corresponding eigenvalue) of the \(2 \times 2\) covariance matrix of frequency and duration. We then define the tie strength between \(i\) and \(j\) as the projection of \(\mathbf{z}_{ij}\) on the principal component \(\mathbf{w}_{ij} = \mathbf{v}_1^T \mathbf{z}_{ij} + w_0\), where we add \(w_0 = \mathbf{v}_1^T \left(-\frac{\bar{f}}{\sigma_f} - \frac{\bar{t}}{\sigma_t}\right)\) (the projection of the feature value for a pair without contacts) in order to have positive tie strengths. The obtained weight is a generic metric that combines the frequency and duration in a scalar value and captures the heterogeneity of node pairs with respect to frequency and duration of contacts\(^4\).

### III. Small-world Structure

Fig. 1 shows as an example the DART contact graph. We observe that there is strong non-random structure. To quantify this structure, we first measure some standard metrics such as average shortest path lengths and clustering coefficients.

The graphs of all scenarios are connected, i.e., there is a path between all node pairs. However, they vary in terms of density (the density \(D\) being the percentage of node pairs for which \(w_{ij} > 0\)): \[D_{\text{DART}} = 0.12, D_{\text{ETH}} = 0.09, D_{\text{GOW}} = 0.04, D_{\text{MIT}} = 0.68.\]

We first compute average path lengths and clustering coefficients. With these properties we can examine the graphs for small-world characteristics. Small-world networks, according to [17], manifest short paths between nodes (a typical property of random, Erdős-Rényi graphs) and high clustering coefficient (tendency of relations to be transitive). The clustering coefficient of node \(i\) is defined as (e.g., [17])

\[C_i = \frac{\text{number of triangles connected to } i}{\text{number of triples connected to } i}.\]

It ranges from 0 to 1, indicating the percentage of triangles which are “closed”. The clustering coefficient of a graph is the average of the nodes’ clustering coefficients. The average path length is the shortest path length, averaged over all connected node pairs.

While clustering coefficient and average path length provide meaningful and comprehensible information about the structure of a binary graph, their respective generalizations (e.g., [18]) to weighted graphs are much less easily interpretable. To maintain the interpretability, we dichotomize our contact graphs by using a threshold to extract the strongest ties (i.e., set them to one and the rest to zero). By doing so, we extract the regular and predictable “backbone” of the contact graph, and dismiss the random unpredictable part (c.f. [19]). To ensure that our results are not distorted by the threshold, we show that the qualitative relations of path length and clustering coefficient stay the same with different thresholds.

Table II shows the average clustering coefficients for different weight thresholds, chosen such that the binary graph densities are fixed to 0.01, 0.02, 0.03 and 0.04. Note that for a random graph (Erdős-Rényi), the clustering coefficient increases linearly with density from 0 to 1. Thus, in a graph where 10% of the node pairs are connected, the expected clustering coefficient is 0.1. The values show that all scenarios are considerably more clustered, strongly suggesting non-random connectivity. We observe that the clustering coefficient of DART, ETH and MIT are very high and strikingly similar, whereas the GOW trace is a bit less clustered. We attribute this to the different nature of the traces: Transitivity of ties in work and home environments is stronger than in social activities captured by Gowalla.

### TABLE I: Mobility traces characteristics.

<table>
<thead>
<tr>
<th>Type</th>
<th># People and context</th>
<th>Period</th>
<th># Contacts total</th>
<th># Contacts per dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP associations</td>
<td>1041 campus</td>
<td>17 weeks</td>
<td>4’200’000</td>
<td>4’000</td>
</tr>
<tr>
<td>AP associations</td>
<td>285 campus</td>
<td>15 weeks</td>
<td>99’000</td>
<td>350</td>
</tr>
<tr>
<td>Self-reported location</td>
<td>473 Texas</td>
<td>6 months</td>
<td>19’000</td>
<td>40</td>
</tr>
<tr>
<td>Bluetooth scanning</td>
<td>92 campus</td>
<td>3 months</td>
<td>81’961</td>
<td>890</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Clustering Coefficient</th>
<th>Avg. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>DART</td>
<td>0.71</td>
<td>7.4</td>
</tr>
<tr>
<td>ETH</td>
<td>0.66</td>
<td>6.1</td>
</tr>
<tr>
<td>GOW</td>
<td>0.28</td>
<td>4.5</td>
</tr>
<tr>
<td>MIT</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^3\)Note that the age of last contact is not suitable for our purpose, since we need aggregate properties over the trace duration.

\(^4\)Note that this framework implicitly assumes stationarity of the underlying mobility process, which is not always true in some traces. In practice (e.g., for protocol design), one can implement a sliding window mechanism.
Looking at the average shortest path length, we see that paths are only few hops long on average. Thus, we observe the small-world behavior, typical for social networks, also in the network of physical encounters.

This finding is related to the report of short opportunistic paths by Chaintreau et. al. [14]. However, there are two main differences to this study which we discuss in the following.

i) [14] measures path length in terms of number of relays using epidemic dissemination (i.e., messages are copied at every encounter). Their result means that short paths exist, when accounting for both, strong and weak ties (pairs which meet often and ones that only meet randomly). Here, we limit the edges to strong ties, and find that paths are still short. This is an important distinction for designing dissemination protocols, where forwarding decisions must be made based on regular encounters and not random, unpredictable ones [19].

ii) The scenarios in [14] are one order of magnitude smaller in number of nodes (MIT, which we also consider, is the largest trace considered there). It is not obvious that the results in [14] would also hold for networks with more nodes (DART) and broader geographic range (GOW).

Note also, that [14] does not account for clustering.

IV. Community Structure

Additionally to the described small-world characteristics, we are interested in the existence of communities [20] in the contact graph. Communities, informally defined as subsets of nodes with stronger connections between them than towards other nodes, are typical for the structure of social networks.

The existence of strong communities in the contact graph has various implications for opportunistic networks: On one hand, it implies high potential for node cooperation and community-based trust mechanisms. On the other hand, it may also imply high convergence times for distributed algorithms since there may be strong bottlenecks between communities.

A. Community Detection Results

To detect communities in the contact graph, we apply the widely used Louvain community detection algorithm [22]. To measure how strongly modular the resulting partitioning is, we use Newman’s $Q$ function [20]:

$$Q = \frac{1}{2m} \sum_{ij} \left( w_{ij} - \frac{d_i d_j}{2m} \right) \delta(c_i, c_j),$$

Note that the existence of community structure is related to a high clustering coefficient, however, strong clustering can have origins other than community structure. For instance in the ring lattice (where the nodes are arranged in a ring and connected to their $K$ (with constant, small $K$, $K \geq 2$) neighbors on the left and right side), without re-wiring, the clustering coefficient is $\frac{K}{2}$ [21], even though there is no community structure.

Since the partitioning of communities depends on the algorithm, we used spectral clustering as a second algorithm for detecting communities. The results are very similar, hence we do not report them here.

B. Intra-Community Structure

A community, by definition, is a strongly connected subgroup of nodes. Hence, we expect intra-community weights (where intra-community weights $w_{ij}$ are those, for which $c_i = c_j$) to be stronger on average than the average of all

$$\sum \delta(c_i, c_j)$$

This metric is sometimes also called node strength, to distinguish it from the degree (number of edges of a node) in binary graphs.
weights. Indeed, Table IV reports that the median\(^8\) of the weights is much stronger within communities than globally. However, we also notice that communities are not completely meshed entities: The density (we define the community density as the percentage of intra-community weights \(> 0\)) is far from 1. This suggests high heterogeneity of weights within communities, which is confirmed by the complementary cumulative distribution function (CCDF) plots of the global and intra-community weights in Fig. 3.

We also observe that the distributions differ between the traces. The straight line in log-log scale implies a power law distribution of the GOW weights. For the other traces, the plots suggest a somewhat thinner tail with two regimes or log-normal shape. Yet, note that the distribution of the global weights is in all cases qualitatively very similar to the distribution of the intra-community weights\(^9\). This is an important observation, as it suggests that there is no fundamental difference between community weights and global weights, other than intra-community weights being stronger on average.

To confirm this visual conclusion, and to characterize the distributions further, we report statistics related to their second (Coefficient of Variation), third (Skewness) and fourth (Kurtosis) moments [23] in Table IV. The high Coefficients of Variation (> 1 means more variation than an exponential distribution) confirm high heterogeneity of weights, both within communities and globally. Further, we notice high Skewness values (2 for exponential, higher positive values imply higher asymmetry towards the right of the mean) and high Kurtosis values (9 for exponential, higher values imply flatter distributions) implying a “fat” tail of weight distributions, both globally and within communities.

Even if a node does not meet all of its community peers, there must still be a reason that it is placed in a certain community: We expect it to have a high average weight towards other nodes in its communities. To verify this, we define the normalized global degree of node \(i\) as its node degree \(d_i = \sum_{j \in N} w_{ij}\), divided by the number of nodes in the network \(|N|\). Similarly, we define the normalized community degree of node \(i\) as the sum of its weights to other nodes of its community \(d_i^{c} = \sum_{c_i = c_j} w_{ij}\), divided by the number of nodes in community \(c_i\).

Table V indeed shows that the median is significantly higher for community degrees. Fig. 4 further plots the CCDFs of the normalized degrees in log-linear scale (notice the difference in scale from Fig 3). From the almost straight lines (particularly in DART and ETH), we visually conclude that the distributions are close to exponential. This is confirmed with the Coefficients of Variation, Skewness and Kurtosis values reported in Table V, which (except for GOW) are close to the values for exponential distributions. Note also that the statistics for global and community degrees follow each other closely, suggesting that the distributions are of the same type. We will discuss the implications of these findings in the following section.

### V. Discussion and Conclusion

We have presented an extensive measurement study of structural properties of contact traces collected in different mobility scenarios. In the following, we summarize our findings and discuss the implications for mobility modeling and for routing protocols for opportunistic networks.

**Small-world:** Short average path lengths and high clustering coefficients show that the graph of wireless contacts has small-world structure. Unlike [14], which only proves the existence of short space-time paths (possibly formed by random, unpredictable contacts), our findings suggest that short paths can in fact be found by complex network analysis based routing protocols [12], [13] that can only infer and exploit strong mobility ties and predictable contacts. This result suggests that the contact graph has good navigability properties [24], an aspect we plan to analyze in the future.

**Heterogenous weights:** Weight distributions show high variance and heavy tails, both, globally and within communities. While this result for global weights is related to heavy tailed inter-contact times reported before [9], [10], it is more surprising for the intra-community weights. Such heterogeneity within communities should be considered when modeling social (group) mobility. Further, it has implications for opportunistic routing protocols: It is not enough to find the community of the message destination. Intra-community routing could help to find a node within a community.

**Degree distributions:** Heterogeneity of degrees is much smaller than heterogeneity of weights and the degree distributions are clearly not scale-free. This raises some questions as
to the efficiency of intra- and inter-community routing schemes based on increasing degree centrality of the relay (as a typical search strategy for networks with scale-free degrees). In future work, we intend to quantitatively investigate, whether such approaches can efficiently navigate the contact graph.

**Similarity of global and community scale:** The similarity of the weight and degree distributions, globally and within communities, suggests that similar routing strategies could be applied on both levels. This finding also hints towards a self-similar structure of the contact graph across different scales, a property which has already been reported for different complex networks [25]. We plan to further investigate the similarity of global and intra-community weight and degree distributions.

Further, we plan to compare the characteristics we found here to those of contact graphs created from synthetic mobility models. Since opportunistic networks research is heavily based on simulation, it is important to have models that accurately reproduce realistic contact structure.

**References**


