Clique-Aware Mobile Social Clouds

Christian Quadri, Matteo Zignani, Sabrina Gaito, Gian Paolo Rossi
Computer Science Dept. , University of Milan
Email: firstname.lastname@unimi.it

Abstract—**The important role played by cliques in identifying cohesive subgroups of people has been theorized and explored by sociologists years ago, but only recently investigated in large-scale social networks. In this paper we focus on the interplay between cliques established by on-phone communications and the urban locations their members share each other. The results about co-located cliques has been achieved through the extensive analysis of a large anonymized dataset of Call Detail Records (CDR) relying on the phone activities of nearly 1 million people in the city of Milan. Taking the cue from the observation of cliques, the paper envisions and designs a novel clique-support service for mobile users by fully exploiting the current virtualization process that is radically transforming the core network of mobile operators. The approach we propose brings together a few important contributions: first, it concretely shows that the current NFV-enabled trend of placing cloud services at the edge of the operator's network is viable and may have a payoff in terms of traffic offloading and improved user's experience; secondly, it demonstrates for the first time that a few typical cloud-based services can effectively be directly performed inside the mobile network by simply leveraging the rich amount of data about users' location and mobility behavior.**

I. Introduction

The real-life sociality of each individual unrolls among friends with strong social ties, is still bound to proximity, which means being near enough to repeatedly encounter the person and to do things together, and gives opportunities to share common ideas and personal feelings with each other. Today's social network operators and service providers willing to deploy cloud-based platforms suitable for supporting real life social interactions are required to tighten their grip on the daily life of their users and keep some synchrony with their social and mobility behaviour. Such a direct drive with the daily life of individuals can only be achieved by performing continuous monitoring of the users' devices and becoming aware of their surroundings through the connectivity infrastructure provided by mobile operators. The result is a growing amount of resource draining interactions that reduce the users' quality of experience, force mobile operator to continuous expensive upgrades and give rise to critical privacy concerns.

The next generation cellular networks, with flexible and decentralized architectures more akin to modern data centers, will provide the connectivity and computing infrastructure where all system and networking issues can be properly addressed, mitigated and solved [1], [2], [3]. However, to benefit of this emerging new service provisioning in the design of services inspired by and tailored on individual's behavior, the research is today challenged by the urgency of better understanding how real life sociality is undertaken and properly drive the design of a digital service and of the underlying network infrastructure, accordingly. In line with these arguments, this paper pursues the following objectives:

- give empirical evidence of the nature of the social interactions among people in real life. We achieve this goal through an extensive analysis of a large anonymized dataset of Call Detail Records (CDR) relying on phone activities (voice, data and text) of nearly 1 million people in the city of Milan.
- define functional and system requirements of a digital platform supporting real life social activities, interactions and encounters.
- envision a service architecture suitable for addressing these requirements. In line with a mobile edge computing approach, we sketch a viable virtualized approach placing the service as close as possible to the end-user at the edge of the mobile operator's core network.

The main contributions of the paper are:

i. We observe that the human sociality mediated by on-phone communications is organized in cliques of small size (we observed cliques ranging from 3 to 9 people) and with intense internal interactions revealing strong social ties among people belonging to the clique. People in a clique are used to encounter periodically in a variety of city's locations, thus proving the importance of physical encounters in real life sociality and the role of on-phone interactions on capturing mobi-social groups. The interplay between on-phone groups and group meeting is stronger w.r.t. results about a similar correlation measured on single links [4].

ii. Cliques justify the rise of CLique-Aware Mobile Social networks, we name it CLAMS, serving the small community of individuals and providing internal basic services, such as clique interactions, sharing of contents relevant to the clique (namely, photos, video or other contents), and clique specific privacy preservation policies driven by explicit user's consent. During extemporaneous encounters of the persons in a clique, devices' proximity may be opportunistically exploited to provide CLAMS communications. This way CLAMS creates a targeted service which supports the needs of the cliques;

iii. The potentially huge amount of CLAMSs (more than 53.000 have been observed in our dataset) has explicit entailments on system requirements when supporting the interactions between user's device and cloud-based CLAMS service. Efficiency, flexibility and scalability requirements

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advocate a virtualized approach enabling to dynamically place contents as close as possible to the mobile users, and to lower the entire cloud-based CLAMS service next to the users when they encounter each other in a city location. In the perspective of a totally virtualized mobile network, the cloud service may not only be placed next to the operator's data centers, but it can definitely enter it and be placed at dynamically changing levels in the network hierarchy with the aim to optimize resource consumption, reduce latency and ensure traffic offloading from the operator's core network. In line with these arguments, we let the cloud service cooperate with the operator's core functionalities to orchestrate the placement of the CLAMS cloud thus finding the best trade-off between network resource consumption and user's perceived service quality. This way, for instance, when the members of a clique are co-located, the cloud service can be placed at the edge of the core network [5], [2] to ensure low latency interactions and efficient content sharing. Co-location is frequent among friends and is common in workplaces, where members of a team daily share the same area and perform intense interactions. When the devices of a clique happen to be under the coverage area of a single cell tower, the relevant device-to-device communications can be seamlessly performed via Direct-LTE [6] or opportunistically. The paper describes a NFV/SDN-based architecture supporting dynamic placement of CLAMS through cooperation between network and cloud operators.

II. Mobi-social groups

A cloud-based platform supporting social interactions cannot disregard the role of social groups as the main constituent of its infrastructure. Social groups are often identified by the notion of cohesive subgroups, i.e. subsets of individuals among whom there are frequent and relatively strong interactions. In these groups beliefs, interests and idea are often very homogeneous due to the pressure towards uniformity and group standards exerted by intense interactions [7]. Favorite places are among the interests of a cohesive group. In fact, shared places encourage the formation and the strengthening of social relationships and, conversely, groups could choose a specific place to better express themselves.

Through mobile phone data we are able to highlight the interplay between cohesive groups and people mobility. Although on-phone communications capture a part of all social interactions, mobile phone data are inclined to trusted communications since people are not willing to share their private phone number with everyone. This way we rely on calls and text-messages to identify cohesive groups. At the same time we exploit the localization provided by the network infrastructure to reconstruct the mobility patterns of the group members. Specifically we proceed in our analysis by *i*) identifying close groups through the extraction of maximal cliques; *ii*) studying how interactions inside a group are distributed and finally; *iii*) mapping a clique to the places it visits, finding what we call 'mobi-social' groups.

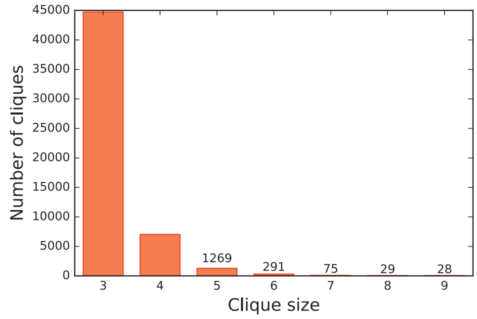


Fig. 1: Clique size distribution.

A. Dataset

Our mobile phone dataset [8] consists of Call Detail Records (CDRs) containing voice-call, text and data activities of nearly 1 million mobile subscribers in the Milan metropolitan area. The records span over 67 days, from March 26 to May 31, 2012; a period long enough to reconstruct most of the on-phone social relationships, as observed in Onnela *et al.* [9] (the statistical characteristics of the network largely saturate in a two-months-long sample). Whenever a voice/text call is issued, a CDR entry is created as a 6-ple $t_{CDR} = \langle s, r, t_{start}, d, cell, area \rangle$, where s and r respectively represent the sender and the receiver of the call/sms, t_{start} is the initial time of the activity (when the call starts or a SMS is sent), d is the duration and $cell$ is the serving cell the user s is attached to. The field $area$ indicates the location-name attribute related to the $cell$, e.g. street/square name or city's zone, that represents a coarse grain division of the city region.

We discovered that nearly 40% of calls have duration equal to 0. Besides missed or unanswered calls, 0-duration calls are reckoning with a common practice in Italy to use rings for implicit communications ("Call me back soon", "I'm just arrived", etc.). Due to the ambiguity of 0-duration calls in the analysis of social interactions, we discarded them from the dataset which finally turns out to be composed of 41 millions calls and 20 millions SMS. We also filtered out calls involving other mobile operators, both incoming and outgoing, thus maintaining only activities involving subscribers of the same operator. This way we eliminate the bias between operators; in fact, we have a full access to the call/SMS records of one operator, while partial access to the calls issued towards subscribers of other competitors.

Unlike previous studies where cell tower may cover a zone as wide as a few kilometers [10], the dataset we are leveraging reports data about cell towers inside a city space where a very small coverage radius, of one or few hundred meters, is adopted. This characteristic, combined with the knowledge of cliques, is a powerful enabler to study the off-line social life of tight-knit groups as information on both their communications and meetings can be mined from the dataset. In fact, we argue that, when people with strong social relationships happen to be contemporaneously co-located, they are more likely to have a social encounter and a face-to-face interaction than being co-

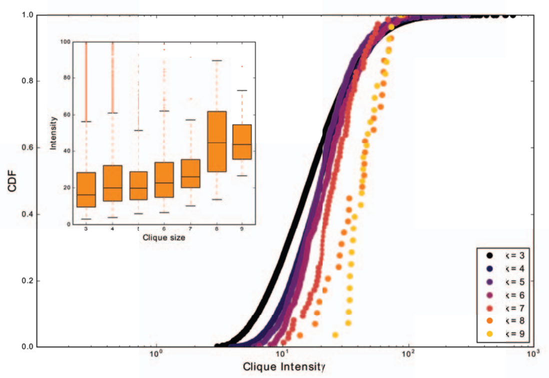


Fig. 2: Distribution (CDF) of the clique intensity as a function of the clique size (k). The inset figure shows the correlation between the clique size and the median clique intensity. The boxes contain values between the first and the third quartile.

located by chance.

B. Clique analysis

We construct the call/SMS undirected weighted graph $G(N, E, W)$ where N is the set of the mobile operator subscribers and E is the set of ties between them, where a link exists between node i and node j if at least three communications, either voice call or text messages, with an overall duration greater than a minute, have been exchanged between the two end-nodes. The order of the resulting network is 289448, while its size is 429273. The weight $w_{i,j}$ of a link (i, j) is an integer number equal to the overall number of communications, voice calls and text messages, between the two nodes.

We rely on the notion of clique to identify cohesive subgroups on the mobile phone graph. To this aim on $G(N, E)$ we performed an adaptation of the Bron and Kerbosch's algorithm [11] to find all the maximal cliques in an undirected graph, i.e. the maximal fully connected subgraphs in the network. Although the worst-case running time of the algorithm is exponential on the number of nodes, in practice it has been demonstrated to run very fast on real networks. The algorithm returns a set C of maximal cliques, whose elements will be indicated by c_i.

1) Do cliques exist?: Overall, we observed 53437 maximal cliques whose size (k) is greater than 2. 122.027 people, 29.4% of all users, are involved in at least one clique, a very high percentage if we mind the limits of mobile phone data: only communications between users of the same mobile operator and on a limited geographical area are recorded. The same holds for links since the 44% of network ties are intra-clique. This very first result confirms the presence of strongly cohesive groups in mobile phone graphs and highlights the importance of cliques in the people's sociality expressed through on-phone communications.

The distribution of clique size is in line with other studies [9], [10], [12], too. As shown in Figure 1, very small cliques ($k = 3, 4$) are predominant. They represent the reference group from where an individual is particularly likely to seek advice or support when needed since the corresponding links represent very strong social relationships. In particular the prevalence of triangles ($k = 3$) highlights that, also in call graphs, the triadic closure process is very likely to happen and act on the network structure. Fig.1 also indicates that larger cliques are less widespread and they more likely represent cohesive groups of interest than familiar or friendship tight groups. No cliques larger than 9 was observed, however we suppose that larger cliques could actually be observed by combining phone data of other mobile operators.

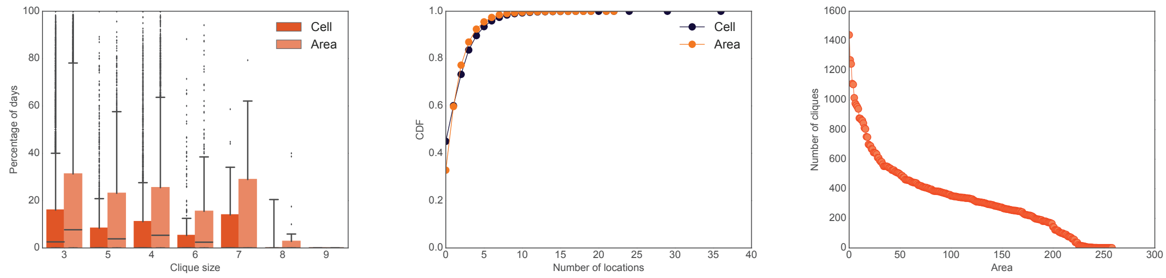
2) Clique strength: One of the properties characterizing cohesive subgroups is the higher frequency of ties among their members compared to the remainder of the network. In line with the previous works on cliques in call graph [9], we compute the clique intensity int to assess the propensity of communicating inside a clique. The clique intensity of a clique c_i is defined as the geometric mean of its link weights:

$$int(c_i) = \left(\prod_{(i,j) \in E(c_i)} w_{i,j} \right)^{1/|E(c_i)|} \qquad (1)$$

where $E(c_i)$ denotes the links forming the clique c_i. Fig.2 shows the cumulative distribution function (CDF) of the clique intensity for the different values of the clique size. Globally, we observe that members in the cliques are quite interactive since the median is equal or greater than 20 interactions for each distribution. Thus, on average, each pair in a clique has communicated more than 20 times in two months. Moreover the range of the intensity reduces as the clique size increases. For instance, triangles include both scarcely (3 interactions per pair on average) and very active (> 600 interactions per pair) 3-ples, while the intensity of larger cliques lies within a smaller range ($25 - 60$ interactions per pair).

As shown in the inset boxplot of Fig.2, we make the correlation between the clique size and the intensity more explicit. The median intensity increases as the size increases, specifically it doubles for the largest cliques. From the network operator viewpoint these large cliques represent a strategic target (marketing, premium services) due to their frequent communications and their cohesiveness, while from a sociological viewpoint the increasing trend of the intensity suggests that maintaining large strongly cohesive groups can be highly demanding in terms of communications and resource consumption, thus advocating specific support by the cellular network infrastructure.

3) Clique meeting places: Mobile call data have been exploited in recent years to extract the relation between people's sociality and mobility. Most of researches focused on dyads and found out that people having a social relationship are more likely to share spaces than unrelated ones, although all these studies have been using a coarse spatial granularity in the mile/km scale. In [13] we observed a weak correlation between social and spatial communities as detected on the same dataset we are using here with a finer granularity ensured by the dense



(a) (b) (c)

Fig. 3: a) Percentage of cliques that meet. b) Distribution of the number of locations (cell/area) per clique. c) Number of cliques meeting in each area.

placement of urban cell towers. Nonetheless, communities remain quite loose organizations that only sporadically gather in a place to perform common activities. By contrast, at the network mesoscopic scale, cliques are more interesting when a strong socio-spatial connotation is needed. We adopt the following methodology to detect clique co-location. For each clique we reconstruct the mobility trace of each user starting from the CDRs, and we transform it as follows: we convert each point, identified by triplet $\langle t, cell, area \rangle$, in a time interval assuming that if the user was in a cell at time t she/he was in that cell from $t - \Delta$ until $t + \Delta$. In this paper we use $\Delta = 30$ minutes in line with [4]. Each time interval maintain the same location attributes (cell and areas) of the trace point from which is generated. Then we merge all the traces of the members of the clique, by retaining only the time overlapping intervals that share the same location attributes. In the following we consider two levels of clique co-location, cell-tower and area. Cell co-location, i.e. the strictest one, implies that, for all the retained time interval, the cell attribute must be the same across all clique members, while in case of area co-location this restriction is limited to the area attribute.

Our findings show that 57.1% of cliques meet at least once in the considered time frame, that is an impressively high amount when considering the network sparsity. The result confirms that there is a strong correlation between on-phone interactions and real life encounters. The percentage of meeting cliques per clique size is reported in Fig.3a. The likelihood of having all clique members gathered in a place at the same time decreases with larger cliques.

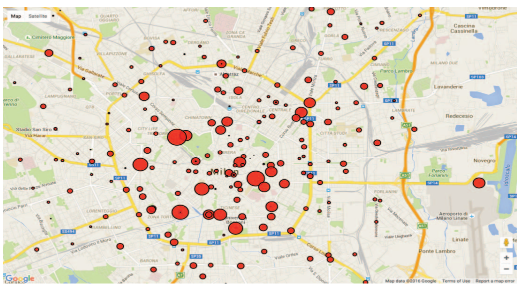


Fig. 4: City map with places of encounter.

4) Social urban spaces: In Fig.3b and Fig.3c the number of locations visited by a clique and the number of cliques meeting in each area are reported, respectively. A visual representation can be seen in Fig.4 where most social urban spaces are reported on the city map. Fig.3c and the map in Fig.4 highlight the fact that some city locations are more favored that others for clique encounters and therefore, indirectly, that cities have places more social than others.

III. NFV-based Architecture for CLAMS

The results of the CDR analysis described in the previous section give a quantitative evidence of how social interactions are performed in real life. We show that interactions are often performed within cliques of individuals with strong social/professional ties and that persons engaged in a clique are also used to encounter each other in different locations of a city, i.e. they are co-located. Interactions in a clique are performed either by voice call or text message, or generate data traffic when contents are shared. Traffic is generated when the persons are spread in different locations of the city and continues even when they are co-located.

In such a scenario, we can envision that the traffic load created by the interactions within a clique is intended to grow sharply with the growth of people sharing resource-draining contents (for both leisure and work), playing distributed games, or as soon as virtual reality will become a common tool for social engagement. Mobile operators are already designing the next generation cellular networks to achieve higher standards of flexibility, scalability and performance through virtualized architectures more akin to data centers. This radical transformation will provide the connectivity and computing infrastructure where all these emerging system and networking issues can be solved. Similarly, cloud-based operators will be urged to collaborate with network operators to ensure the best quality of experience to their users, while optimizing resource consumption and reducing time latencies among interacting people. As shown by this paper, cliques are social aggregations deserving this type of care by any cloud-based service provider.

In this Section we provide the description of the architecture exploiting the underway evolution of cellular networks to properly support interactions among people belonging to a clique, i.e. we provide the CLAMS supporting architecture.

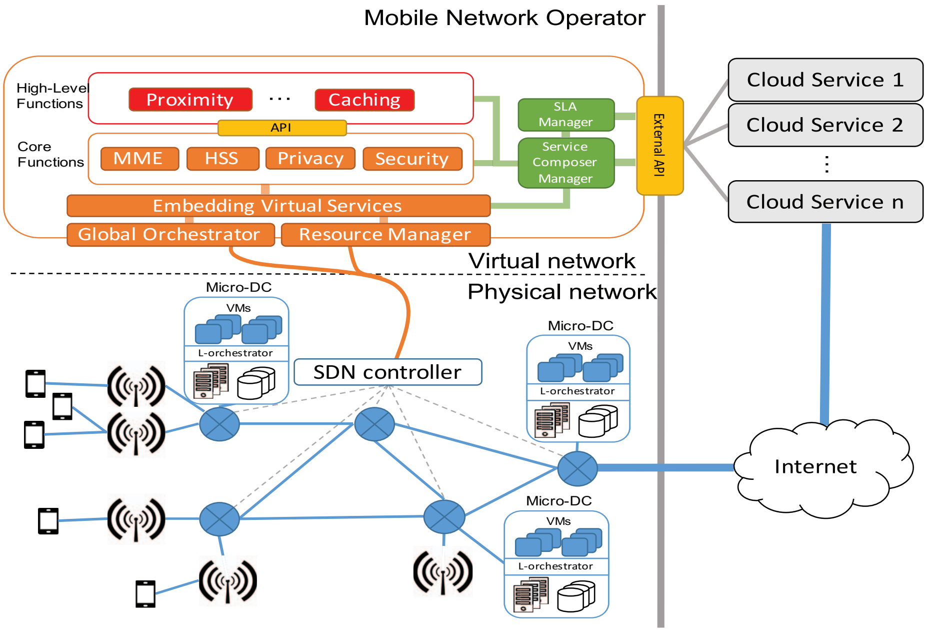


Fig. 5: CLAMS architecture.

At the hearth of this idea lays the need to provide a framework enabling network and cloud operators to negotiate the service agreement, package it with the instantiation of the cloud service and let the network operator to orchestrate the placement of the embedded service in order to satisfy the service requirements and optimize the resource utilization. The architecture is coherent with the current evolution of mobile networks to meet the 5G requirements of flexibility, scalability, small delay and high bandwidth. Our approach has been inspired by [14] where a new architecture, based on network function virtualization (NFV) and software defined networking (SDN), is presented without requiring control and data planes; rather, they are tailored according to the requirements of specific applications and devices. In line with the proposal, any network function can be dynamically instantiated within the cloud infrastructure to satisfy specific application and device performance and relevant functional requirements. Relying on this approach, our proposal enables CLAMS to be easily deployed and managed in a virtualized environment.

A. *Architecture overview*

The Fig. 5 shows an overview of the architecture supporting the CLAMS service. The network architecture combines both *Physical* and *Virtual* elements. The physical network contains all resources – computational, storage and networking – providing connectivity to the users, and implements the data plane protocols. The network nodes are compatible with SDN standards, e.g. Openflow, and are all managed by a SDN controller. Inside the physical network we place micro data centers (Micro-DC), each handling one or more access nodes and covering different geographical areas (preferably overlapped to favor load balancing). The network operator could decide to assign a Micro-DC to a single area, or Tracking Area, or even to a single cell tower, for dealing with the traffic burden and requirements that crowded locations of a city bring together, like the case of the most social places we identified in the previous section or whenever popular events are organized in a city. Micro-DCs have computational and storage resources managed by a local orchestrator (L-orchestrator) and they are able to host virtual instances of network functions (e.g. MME, HSS and security) as well as virtual packages embedding cloud services and serving cliques of users, either spread in different locations of the city or co-located.

On top of the physical network, the virtual network is composed of different modules in charge of managing the physical network and orchestrating the virtual services that, in the perspective of this proposal, can be both internal and external to mobile operator. The three modules at the edge between physical and virtual networks have the responsibility of managing physical resources. In particular, the *Global Orchestrator* supervises the allocation and the deployment of virtual resources, the *Resource Manager* collects and processes all status information of the allocated resources, the *Embedding Virtual Services* maps the virtual services on the physical resources on the base of the information provided by the resource manager. A set of *Core Functions* lays on top of the edge modules and constitutes the template of the current LTE core network functionalities. These templates will be configured and combined in service packages according to the global orchestration strategy during the deploying phase. Core Functions may be combined with *High-level Functions* to provide templates of added-value services, whose configuration is still performed by the global orchestrator during the deploying phase. Moreover, cloud service providers can seek improved user's quality of experience and service provisioning by requiring to wrap cloud-specific functions in combination with both core and higher functions. The obtained service package is thus embedded and deployed by means of the edge services. For instance, a clique of CLAMS can be instantiated in a package together with Proximity and Caching Higher Functions, and with most of the Core Functions.

The cloud-based service provider can interact with the mobile operator through the *Service Composer Manager* that offers a sort of dashboard interface from where the cloud provider is able to wrap and tailor services by simply leveraging functions and services provided by the network operator. The Service Level Agreement module, *SLA manager*, has been added to regulate the usage of the infrastructure. Both Service Composer Manager and SLA Manager are accessible through a set of API and are needed to negotiate the service quality and compose the cloud service to deploy inside the operator's network.

B. CLAMS services deployment operations

When the CLAMS service provider needs to wrap a clique-specific package inside the operator's network, it directly accesses the service composer manager. The service-specific requirements drive the selection of different cloud and network functions and lead to create the template of the CLAMS service that, if it satisfies the policies defined in the SLA Manager, can be added to the repository – one per each cloud service – of the deployable CLAMS services. While packaging the cloud service, the requirements in terms of bandwidth, delay, computational and storage capabilities are specified.

The cloud service provider can also specify a set of rules, within the negotiated Service Level Agreement, to apply when the service is deployed, e.g. to optimize content access and interactions when clique members are co-located, or to characterize the traffic among clique components. The activation of a set of rules triggers the deployment phase, a message is sent to the Embedding Virtual Service module that performs the embedding of the required CLAMS service into the physical network. The Global Orchestrator is then activated, operates the deployment of the virtual instances and informs the SDN controller about the required links. At this point, the CLAMS service is ready to be used by users.

Although the described architecture enables to sink cloud services into the depths of the operator's core network, no sensible information are, interestingly, shared between the two operators; for example, the users' location remains in the domain of mobile operators, while the cloud service provider is unaware of where the CLAMS and relevant users are placed. Moreover, the rules to preserve privacy are managed by the cloud operator and deployed accordingly.

IV. Concluding remarks

In this work we show that on-phone interactions bring together the formation of cohesive social groups of persons, or cliques, and we give evidence of them. Moreover, we show that people engaged in cliques are also very likely to meet each other in different locations of the city space, thus enabling the identification of the most social locations of the city, i.e. the places where cliques are more likely to encounter. These information are relevant whenever new socio-techno-driven services have to be designed and deployed by either mobile or cloud operators. By exploiting the underway radical transformation of the core network of mobile operators, we provide a virtualized network architecture enabling cooperation between mobile and cloud operators to embed cloud services into the mobile network thus ensuring high user's experience, reducing resource consumption and minimizing communication latency. All these first results are promising enough to induce us to perform further investigations. In particular, a deep temporal analysis of clique's socio-spatial patterns is needed to better design the architecture, while specific simulation should be performed to quantify the benefits achieved by adding flexible placement in Micro-DC by means of function virtualization.

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