

# Structure and tie strengths in mobile communication networks

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**Electronic databases, from phone to e-mails logs, currently provide detailed records of human communication patterns, offering novel avenues to map and explore the structure of social and communication networks. Here we examine the communication patterns of millions of mobile phone users, allowing us to simultaneously study the local and the global structure of a society-wide communication network. We observe a coupling between interaction strengths and the network's local structure, with the counterintuitive consequence that social networks are robust to the removal of the strong ties but fall apart after a phase transition if the weak ties are removed. We show that this coupling significantly slows the diffusion process, resulting in dynamic trapping of information in communities and find that, when it comes to information diffusion, weak and strong ties are both simultaneously ineffective.**

complex systems | complex networks | diffusion and spreading | phase transition | social systems

Uncovering the structure and function of communication networks has always been constrained by the practical difficulty of mapping out interactions among a large number of individuals. Indeed, most of our current understanding of communication and social networks is based on questionnaire data, reaching typically a few dozen individuals and relying on the individual's opinion to reveal the nature and the strength of the ties. The fact that currently an increasing fraction of human interactions are recorded, from e-mail (1–3) to phone records (4), offers unprecedented opportunities to uncover and explore the large scale characteristics of communication and social networks (5). Here we take a first step in this direction by exploiting the widespread use of mobile phones to construct a map of a society-wide communication network, capturing the mobile interaction patterns of millions of individuals. The data set allows us to explore the relationship between the topology of the network and the tie strengths between individuals, information that was inaccessible at the societal level before. We demonstrate a local coupling between tie strengths and network topology, and show that this coupling has important consequences for the network's global stability if ties are removed, as well as for the spread of news and ideas within the network.

A significant portion of a country's communication network was reconstructed from 18 weeks of all mobile phone call records among  $\approx 20\%$  of the country's entire population, 90% of whose inhabitants had a mobile phone subscription [see [supporting information \(SI\) Appendix](#)]. Whereas a single call between two individuals during 18 weeks may not carry much information, reciprocal calls of long duration between two users serves as a signature of some work-, family-, leisure-, or service-based relationship. Therefore, to translate the phone log data into a network representation that captures the characteristics of the underlying communication network, we connected two users with an undirected link if there had been at least one reciprocated pair of phone calls between them (i.e.,  $A$  called  $B$ , and  $B$  called  $A$ ) and defined the strength,  $w_{AB} = w_{BA}$ , of a tie as the

aggregated duration of calls between users  $A$  and  $B$ . This procedure eliminates a large number of one-way calls, most of which correspond to single events, suggesting that they typically reach individuals that the caller does not know personally. The resulting mobile call graph (MCG) (4) contains  $N = 4.6 \times 10^6$  nodes and  $L = 7.0 \times 10^6$  links, the vast majority (84.1%) of these nodes belonging to a single connected cluster [giant component (GC)]. Given the very large number of users and communication events in the database, we find that the statistical characteristics of the network and the GC are largely saturated, observing little difference between a two- or a three-month-long sample. Note that the MCG captures only a subset of all interactions between individuals, a detailed mapping of which would require face-to-face, e-mail, and land line communications as well. Yet, although mobile phone data capture just a slice of communication among people, research on media multiplexity suggests that the use of one medium for communication between two people implies communication by other means as well (6). Furthermore, in the absence of directory listings, the mobile phone data are skewed toward trusted interactions (that is, people tend to share their mobile numbers only with individuals they trust). Therefore, the MCG can be used as a proxy of the communication network between the users. It is of sufficient detail to allow us to address the large-scale features of the underlying human communication network and the major trends characterizing it.

## Results

The MCG has a skewed degree distribution with a fat tail (Fig. 1A), indicating that although most users communicate with only a few individuals, a small minority talks with dozens (4, 7). If the tail is approximated by a power law, which appears to fit the data better than an exponential distribution, the obtained exponent  $\gamma_k = 8.4$  is significantly higher than the value observed for landlines ( $\gamma = 2.1$  for the in-degree distribution; see refs. 8 and 32). For such a rapidly decaying degree distribution, the hubs are few, and therefore many properties of traditional scale-free networks (33), from anomalous diffusion (9) to error tolerance (10), are absent. This decay is probably rooted in the fact that institutional phone numbers, corresponding to the vast majority of large hubs in the case of land lines, are absent, and in contrast with e-mail, in which a single e-mail can be sent to many recipients, resulting in well-connected hubs (1), a mobile phone

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Abbreviation: MCG, mobile call graph.

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with the celebrated role of weak ties in information access (17, 19), we find that both weak and strong ties have a relatively insignificant role as conduits for information (“the weakness of weak and strong ties”), the former because the small amount of on-air time offers little chance of information transfer and the latter because they are mostly confined within communities, with little access to new information.

To illustrate the difference between the real and the control simulation, we show the spread of information in a small neighborhood (Fig. 4 *E* and *F*). First, the overall direction of information flow is systematically different in the two cases, as indicated by the large shaded arrows. In the control runs, the information mainly follows the shortest paths. When the weights are taken into account, however, information flows along a strong tie backbone, and large regions of the network, connected to the rest of the network by weak ties, are only rarely infected. For example, the lower half of the network is rarely infected in the real simulation but is always infected in the control run. Therefore, the diffusion mechanism in the network is drastically altered when we neglect the tie strengths responsible for the differences between the curves seen in Fig. 4 *A* and *B*.

## Discussion

Although the study of communication and social networks has a long history, examining the relationship between tie strengths and topology in society-spanning networks has generally been impossible. In this paper, taking advantage of society-wide data collection capabilities offered by mobile phone logs, we show that tie strengths correlate with the local network structure around the tie, and both the dyadic hypothesis and the global efficiency principle are unable to account for the empirical observations.

It has been long known that many networks show resilience to random node removal, but are fragile to the removal of the hubs (10, 28–30). In terms of the links, one would also expect that the strong ties play a more important role in maintaining the network's integrity than the weak ones. Our analyses document the opposite effect in communication networks: The removal of the weak ties results in a phase transition-like network collapse, although the removal of strong ties has little impact on the network's overall integrity. Furthermore, we find that the observed coupling between the network structure and tie strengths significantly slows information flow, trapping it in communities, explaining why successful searches in social networks are con-

ducted primarily through intermediate- to weak-strength ties while avoiding the hubs (3). Therefore, to enhance the spreading of information, one needs to intentionally force it through the weak links or, alternatively, adopt an active information search procedure.

Taken together, weak ties appear to be crucial for maintaining the network's structural integrity, but strong ties play an important role in maintaining local communities. Both weak and strong ties are ineffective, however, when it comes to information transfer, given that most news in the real simulations reaches an individual for the first time through ties of intermediate strength.

The observed coupling between tie strengths and local topology has significant implications for our ability to model processes taking place in social networks. Indeed, many current network models either assign the same strength to all ties or assume that tie strengths are determined by the network's global characteristics, such as betweenness centrality. In addition, some of the most widely used algorithms used to identify communities and groups in complex networks use either betweenness centrality (16) or are based on topological measures (31). Our finding that link weights and betweenness centrality are negatively correlated in mobile communication networks, together with the insights provided by the visually apparent community structure (Fig. 2), offer new opportunities to design clustering algorithms that are tailored to communication networks, and force us to reevaluate many results that were obtained on unweighted graphs. Putting the structural and functional pieces together, we conjecture that communication networks are better suited to local information processing than global information transfer, a result that has the makings of a paradox. Indeed, the underlying reason for characterizing communication networks with global network concepts, such as path length and betweenness centrality, is rooted in the expectation of communication networks to transmit information globally.

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