A Framework for Analysing Dynamic Communities in Large-scale Social Networks

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Abstract: Telecommunications companies must process large-scale social networks that reveal the communication patterns among their customers. These networks are dynamic in nature as new customers appear, old customers leave, and the interaction among customers changes over time. One way to uncover the evolution patterns of such entities is by monitoring the evolution of the communities they belong to. Large-scale networks typically comprise thousands, or hundreds of thousands, of communities and not all of them are worth monitoring, or interesting from the business perspective. Several methods have been proposed for tracking the evolution of groups of entities in dynamic networks but these methods lack strategies to effectively extract knowledge and insight from the analysis. In this paper we tackle this problem by proposing an integrated business-oriented framework to track and interpret the evolution of communities in very large networks. The framework encompasses several steps such as network sampling, community detection, community selection, monitoring of dynamic communities and rule-based interpretation of community evolutionary profiles. The usefulness of the proposed framework is illustrated using a real-world large-scale social network from a major telecommunications company.

1 INTRODUCTION

A manifold of phenomena in the real-world can be naturally represented through dynamic graphs, which are able to capture the state of the underlying network at different moments in time. It has been shown that several real-world networks display community structure (Newman and Girvan, 2004). Communities can be defined as a set of entities that are more connected with each other than with other entities in the network. The problem of community detection has been widely studied in the literature (Fortunato, 2010) but typically the proposed methods provide a static representation of the community structure in the network at a given time point. However, most networks have a dynamic nature, since they undergo frequent changes, featured by a series of temporal events, such as growth, decay or dispersion.

From a business perspective, analysing how communities of customers evolve and behave over time is relevant because it allows, for instance, to understand changes in customers' consumption patterns and get insight into which communities are growing and which ones are fading. This sort of information is useful to redefine marketing strategies, identify influential customers or customise promotional campaigns according to characteristics shared by customers belonging to a given community. Marketeers can also take actions to proactively prevent customer churn and devise recommendation systems of products and services that improve the quality of the consumption experience. Hitherto, studies involving social networks of customers have focused on the churn prediction problem (Verbeke et al., 2014) and on the detection of influential nodes for viral marketing (Domingos and Richardson, 2001; Wang et al., 2010). Here, we address a more general problem, related to the detection, selection, dynamic analysis and interpretation of relevant communities of customers, by proposing a novel and integrated business-oriented framework for dynamic community mining in large social networks. The insights provided by the application of our framework can be harnessed and used as input to solve the aforementioned marketing problems.

The problem of tracking communities over time is not new and several methodologies have been proposed to this end (Berger-Wolf and Saia, 2006; Asur et al., 2009; Brodka et al., 2013; Oliveira et al., 2014).

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Generally, these methodologies rely on analysing the community structure of the dynamic network at consecutive time points over the time span. However, these methods may not be well suited for large-scale networks, with thousands or hundreds of thousands of communities. As we enter the era of Big Data, our capacity to accumulate and store data has increased considerably. The size of data poses challenges to conventional methods and hampers the ability to process and extract actionable knowledge from data. Besides, these methodologies lack strategies to effectively extract knowledge and insight from the analysis, since they focus on the description of the life-cycle of communities and neglect the community profiling step. These constraints call for upgrades and improvements of the traditional methods. In this context, we propose an integrated business-oriented framework to select, monitor and characterise evolving communities in large-scale social networks. Although our framework is built on existing methods, it is novel in the way it integrates them, thus offering a complete step-by-step procedure to extract valuable business insight from the analysis of massive social networks. To the best of our knowledge, we are also the first to propose a business interpretation of the communities evolution. The framework was empirically applied to a large-scale social network from a major telecommunications company. The remaining paper is structured as follows. In Section 2, the foundations of the framework are explained. The proposed framework is described in Section 3 and the case study in which the framework was applied is presented in Section 4. We conclude and discuss the results in Section 5.

2 BACKGROUND

Finding the community structure of a network is a prevalent strand of research because it allows a high-level exploration of the network and a better understanding of its overall structure. Besides, the community structure can represent a summary of a large network, uncovering hidden properties of its elements without loss of personal information. However, although there are several different approaches to community detection, the nature of the problem makes it a complex one. Not only because of the inherent subjectivity and lack of a consensual definition of *community*, but also due to the need for efficiency posed by the increased data availability (Fortunato, 2010). Furthermore, people usually belong to different communities (*e.g.*, family, friends, work), which leads to an overlapping structure of communities (Palla et al., 2005). As opposed to typical clustering analysis approaches, community detection algorithms do not usually incorporate information about the attributes of nodes, focusing essentially on the link structure of the network. There are different approaches to community detection, such as hierarchical clustering, clique-based methods, divisive algorithms (Girvan and Newman, 2002), partitional clustering or modularity optimisation (Newman and Girvan, 2004). The community detection algorithm adopted in our framework is based on the latter. Formally, modularity measures the deviation from the possibility of links of communities having been generated by the natural community structure and the possibility of those links having been randomly generated. Modularity has been used for comparing the quality of partitions generated by different methods, but it is also an objective function for several community detection algorithms that is intended to maximize. Blondel et al. (2008) introduced the Louvain method for the detection of communities in large-scale networks. The Louvain method is an heuristic method based on a greedy hierarchical optimisation of the modularity function. In the hierarchical structure, the network displays several levels of partitions, where small communities are merged into larger ones. The algorithm is non-deterministic and order-sensitive, so it does not guarantee a maximum global modularity. Nonetheless, it is able to discover high-quality network partitions, as measured by the modularity function, beating any other algorithm in terms of computational time (Blondel et al., 2008). Besides, it is highly intuitive and easy to implement. These characteristics motivated the choice of the Louvain Method for performing community detection in this work. The algorithm comprises two phases that are iterated until no more modularity gains can be achieved. Initially, the algorithm unfolds the communities, performing a local modularity optimisation. Then, the network is rebuilt, with the nodes being the communities detected in the first phase. The size of the hierarchy is given by the number of combinations of these two phases.

Networks have a dynamic nature. As a consequence, the corresponding community structure evolves over time. Everyday there are events that change a person's life in some way, and eventually it may affect that person's relationship with other people in the same community he belongs to. Hence, traditional methods for community detection must be updated or, alternatively, complemented with methodologies for monitoring the dynamics of communities. The typical strategy to analyse the evolution of communities over a given time span is to take snapshots of the network at consecutive time points and, then, to detect communities at each one of these snapshots

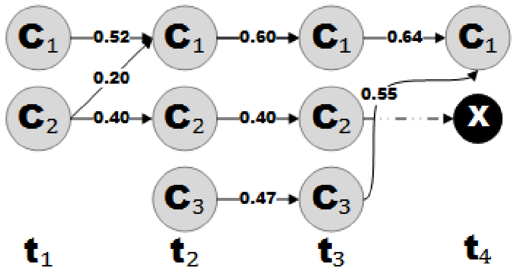

Figure 1: Representation of the transitions and the life-cycle of communities in a time span comprised of four time points. For instance, the life-cycle of C_3 is: it firstly appears in t_2 and survives from t_2 to t_3 into C_3, keeping 47% of its previous elements. From t_3 to t_4, C_3 merges with C_1, giving rise to community C_1 in time point t_4.

(Brodka et al., 2013; Oliveira et al., 2014). By comparing the proportion of shared elements by instances of communities found at consecutive time points, it is possible to detect and categorise the transitions undergone by the communities.

In our framework, we apply the MECnet framework (Oliveira et al., 2014) to monitor the evolution of communities. The methodology of MECnet explores the concept of community mapping by using conditional probabilities. Each pair of possible connections between communities detected at consecutive time points is evaluated based on the proportion of mutual elements shared by both communities. This mapping procedure enables the detection of transitions, which are further used to describe the life-cycle of each dynamic community. The life-cycle summarises the evolution of the dynamic community over the time span (see Figure 1).

In the MECnet framework, the taxonomy used for the evaluation of transitions at consecutive time points consists of five external events: birth, split, merge, survival and death. These events were formally defined by Oliveira and Gama (2010).

3 FRAMEWORK

In this section, we explain each step of the proposed framework for analysing the dynamics of communities in large-scale networks. This framework covers the following five main steps. 1) An unbiased sampling method for both direct and undirected large-scale networks is applied; 2) The Louvain method is run for each snapshot of the sampled network in order to identify communities; 3) Due to the large number of communities typically discovered during the community detection stage, the communities are further filtered according to two business criteria explained ahead; 4) The selected communities are monitored over the time span using the MECnet framework; 5) A community profiling is performed, in order to evaluate and understand the evolution of communities. These steps will be detailed in the next subsections.

The analysis of large-scale networks requires large working memory and powerful processors to extract useful knowledge from these data. However, not all companies have access to these resources, or the time needed to perform the analysis prevents them to get insight from the data in a timely manner. One possible way to circumvent this problem is to focus the analysis on a representative sample of the full network. The goal of sampling techniques is then to obtain a representative fragment of the network that keeps its structural properties.

The Metropolis-Hastings Random Walk (Gjoka et al., 2010) is an unbiased sampling method that provides good results that works as follows. First, it considers a node v from the network and sets a stopping criterion. While this criterion is not met, the algorithm (i) searches and randomly selects a node w, from the neighbours of v, and generates an α from the uniform distribution $U(0,1)$; (ii) compares α with $\frac{k_v}{k_w}$, where k_v and k_w represent the number of neighbours of v and w, respectively; (iii) if $\alpha \leq \frac{k_v}{k_w}$ then v is accepted and included in the sample, turning w into the reference node; otherwise, another w is picked from the neighbours of v. This "if clause" is what keeps the algorithm from biasing to nodes with a high number of neighbours.

After extracting a sample of the network, the communities are detected at each considered time point, using the Louvain Method (Blondel et al., 2008). The algorithm takes as input a weighted edge list. The algorithm associates to each network element the index of the community that it belongs to and it also displays the modularity of the generated partition. Figure 2 shows the representation of a network and its underlying communities.

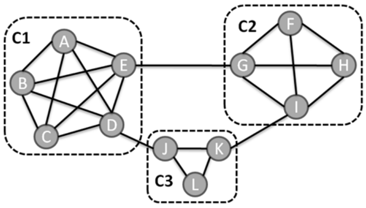

Figure 2: Representation of a network and its underlying communities: C_1, C_2 and C_3 (adapted from Oliveira and Gama (2012)).

In large-scale networks, community detection algorithms typically generate partitions with thousands, or hundreds of thousands, of communities. Since it is not feasible to analyse the whole set of communities and given that the majority of communities is not interesting from the business point of view, it is important to incorporate a community selection step in the process. In the proposed methodology, we perform community selection based on two criteria: (i) the size of communities, and (ii) a RFM (Recency, Frequency, Monetary) model.

In real-world large-scale social networks, such as telecom graphs, the size distribution of the detected communities usually follows a power-law (Nanavati et al., 2008). A power-law is a relation between two variables that occurs when one is the power of the other, drawn from a probability distribution $p(x) = \beta x^{-\alpha}$, where α is the constant scaling parameter of the distribution. In the particular case of communities, this phenomenon is associated with the sharp positive asymmetric distribution of the number of elements in each community. There are usually a large number of communities containing only a few elements and only a small number of communities with considerable size.

In order to test the hypothesis "the distribution of the size of communities follows a power-law", we run several tests using the *poweRlaw* package, available in the *R* software (Team, 2008). Afterwards, to estimate where to cut the distribution, we first sort the detected communities by decreasing size. Then, we analyse the decay in the number of elements covered in the network, for each percentage of considered communities. The cut is made where a natural break of the distribution occurs, according to the so-called *elbow method*. Although this is an empirical procedure, it is efficient in selecting the communities representing the largest portion of the network.

The RFM (Recency, Frequency, Monetary) model (Birant, 2011) is a marketing strategy used to quantitatively determine the best customers of a company according to the following three components: (i) *recency*, which in the context of our framework refers to the average time elapsed since the last time an element of a community used the service (*e.g.*, average time elapsed between calls); (ii) *frequency*, which is given by the average number of times the elements of each community used the service during a given time span (*e.g.*, average number of calls made in one week) and, (iii) *monetary*, which is given by the total amount spent in the service by the elements of the community (*e.g.*, phone bill).

To implement the model, the values of each one of these components are computed for each community and, then, converted into a score from 1 to 5. For instance, the 20% communities with higher frequency are given a score 5 in the *frequency* component, the next 20% communities are given a score of 4, and so on. An overall score is then assigned to each community, by summing up the scores obtained in each component (*i.e.*, recency, frequency and monetary). In a weighted version of the model (Miglautsch, 2000), each component is multiplied by a weight, which reflects its relative importance.

In the particular case of communities in large-scale networks, the RFM analysis supports the decision about which communities may be discarded from the study, and which communities are worth analysing from the business point of view. In other words, this model provides a simple way to extract the most active and profitable communities of customers, which are the ones more likely to spread positive influence in the network.

The communities selected based on the previous criteria are monitored over time, by applying the MECnet framework. This temporal tracking relies on a prior mapping step, as previously explained in Section 2. The identification of temporal instances of the same community, based on the matching criterion, allows the further identification of transitions and the characterisation of a community's life-cycle.

After analysing how communities evolve over time, it is important to characterise this evolution by creating a profile for each dynamic community. The task of community profiling is important to understand how one community differs from another, as well as to understand the underlying logic of the partitions identified by the community detection algorithm. This profiling step is important to companies because it enables a better understanding of the dynamic community analysis, thus allowing them to more easily act upon these customer communities. Communities are described in operational and relational terms. While the operational description is related to business variables, the relational description is based on classical measures from social network analysis (see Oliveira and Gama (2012) for an overview). In order to find the general profile of communities, several attributes from the elements that compose them are studied, such as frequency and duration of calls, as well as node centrality measures. The profiling task is then performed using decision trees, which can be linearized into interpretable decision rules.

Communities are classified into one of three classes: *growth*, *stagnation* or *decay*, according to their evolution over the time span. The type of evolution exhibited by each community relies on the analysis of their life-cycle (see Sections 2 and 3) and is based on changes in the size of communities (*i.e.*, number of elements) over the time span: Growth, if the community survives with sequential increase in its size; stagnation, if the community survives with slight oscillations in its size; and decay, if the community survives but shrinks in size or splits in two or more communities.

To discriminate between different evolution patterns we use decision trees. In the context of community profiling, this type of model can be used to achieve two main goals: (i) upon arrival of a new element to the network, predict in which community this element fits, using solely its attributes, and (ii) obtain a better understanding of the general properties and interactions among the communities. Each path of the tree, from the root to a leaf, represents a decision rule. Due to their high interpretability, we will use decision rules to generate the profile of each community. This is particularly important because it allows for business users with no technical skills to easily understand the model.

4 CASE STUDY

The proposed framework was empirically applied to a large-scale social network from a major telecommunications company. The dataset contains hundreds of millions of phone call records, which correspond to a six month time span. These call records are mapped into an undirected weighted network, where nodes represent customers (namely, mobile users), links represent phone calls and the weight of the links indicates the frequency of communication among pairs of customers. The network is sparse and is only built implicitly by means of a weighted edge list. The application of the sampling method to the whole network generated a manageable network, with a considerable lower size (see Table 1). The sampled network was broken down by month, originating six subsets that are analysed separately. The size of the sampled networks in each month is given in Table 1. Afterwards, we run the Louvain method, whose results are shown in Table 2. Typically, a good partition of the network in communities should present modularity values above 0.3 (Clauset et al., 2004). The average modularity obtained for each subset of the analysed network was approximately 0.9, which indicates the existence of a meaningful community structure for all analysed time points.

As can be ascertained from Table 2, the number of detected communities is large. However, not all of these communities are interesting or worth analysing. In an attempt to identify the most relevant communities to the telecommunications company, *i.e.*, the largest, most profitable and most active communities, we resort to the criteria introduced in Section 3 to perform the selection. Regarding the first criterion (size of communities), there is empirical evidence that the size of communities follows a power-law distribution with a scaling parameter 1.96, as indicated by 2412 out of 2500 statistical tests. According to the size distribution of the detected communities, only the 3% biggest communities are considered, covering more than 98% of customers in the network.
The set of communities is further restricted by applying a weighted RFM model. This model allows the identification of the most profitable and active communities, discarding the ones that are less interesting for the company. The weights assigned to each one of the RFM components were set by the business intelligence analyst of the telecommunications company based on his domain knowledge. Monetary is the component with the highest weight ($w_{monetary} = 0.6$), followed by recency ($w_{recency} = 0.25$) and frequency ($w_{frequency} = 0.15$). The number of communities which were selected based on these two criteria are: July: 208; August: 210; September: 192; October: 170; November: 170; December: 174.

The dynamics of communities selected in the previous step were analysed using the MECnet framework (Oliveira et al., 2014). In Figure 3, the life-cycle of four stable communities is depicted. From the figure, we observe that the communities are stable over the time span, even though the weight of the edges, *i.e.*, the proportion of mutual elements shared by each pair of communities, is below 0.5. This may be related to the inherent volatility of customers' communication patterns. With the increasing use of comput-

Table 1: Size of the edge list representing the network, in terms of the number of edges and the total phone calls made, from July to December.

Month	**Edges** $\times 10^6$	**Phone calls** $\times 10^6$
July	2.2	21.2
August	2.0	18.2
September	2.0	18.8
October	2.0	19.3
November	2.0	18.0
December	2.9	23.2

Table 2: Number of communities and modularity returned by the Louvain Method, for each month.

Month	**Communities**	**Modularity**
July	7.495	0,90
August	5.033	0,91
September	5.988	0,91
October	5.668	0,90
November	5.678	0,90
December	5.610	0,89

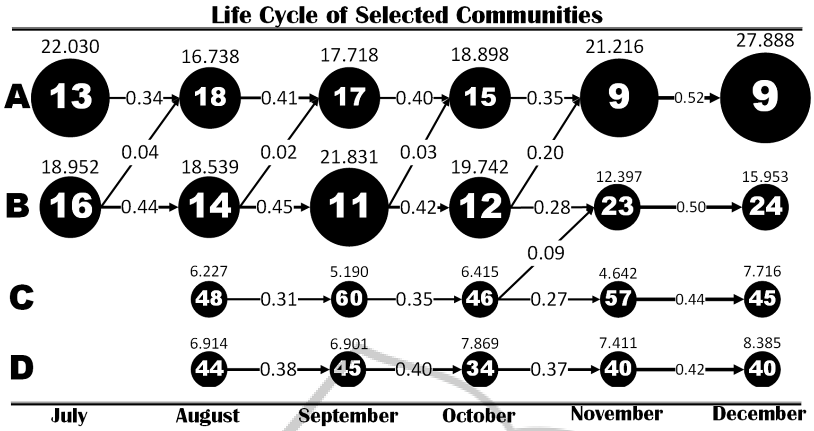

Figure 3: Life-cycle of four communities, from July to December. Each dynamic community is identified by a letter (from A through D). The number inside each community, represented by a circle, symbolises its relative order, according to size, in the corresponding month. The weights of the edges represent the proportion of elements that migrate between communities found at consecutive months. The number above each community represents its size, or number of elements.

ers and other digital devices, people tend to resort to other means of communication, such as online social networks, to communicate with each other. Despite this, there is a core set of customers whose communication patterns persist over time. These are the ones responsible for keeping the community active during the considered time span. From the evolution graph of Figure 3, we can also observe an interesting interaction between community A and community B. From July until November, customers from community B migrate to community A. In October, this migration is stronger because it involves the core customers of community B (*i.e.*, those with highest node centrality) and their direct neighbours. Even though this is an important result, it is also inconclusive, not only due to the subjective nature of the data, but also because of the non-deterministic properties of the community detection algorithm. However, we can conclude that the two communities are close to each other in the network structure, which might explain the strong interaction between their customers.

After selecting the set of interesting communities, a profile of each community is created based on both the classification introduced in Section 3 and the rules generated by a decision tree classifier. In what regards the type of evolution, the analysis of both the life-cycle and size of communities returned the following classification: community A is growing, community B is decaying and communities C and D are stagnated. Also, there is a significant difference between growing and non-growing communities regarding frequency, recency and transitivity (see Figure 4). Frequency and recency were already defined in Section 3. Transitivity is a social network analysis measure, which gives the probability of two individuals that are connected to a third individual, to be also connected to each other. From Figure 4, we deduce that growing communities are associated with a higher average frequency of calls, a higher transitivity and a lower latency of calls made by their elements. In other words, growing communities are the most active ones and display a more consistent topology. Besides performing this classification, we also applied a decision tree classifier, where each observation is a customer and the class is the community the customer belongs to. For this task, we focused on the core customers of each community, because these do not change their community membership over the considered time span. In theory, these persistent customers are the ones that better reflect the general properties of the communities. In order to apply the decision tree, first we perform feature selection using a Manhattan distance based algorithm. The chosen variables were: (i) average frequency of calls, (ii) average duration of calls (in seconds), (iii) degree centrality, (iv) betweenness centrality, (v) closeness centrality and (vi) local transitivity. Then, it is built a fit classification model, using the *c5.0* algorithm (Quinlan, 1993). For evaluating the classifier we used the holdout method, with 70% of the dataset used for training and 30% for test. Below are the generated rules for the communities depicted in Figure 3, which obtained the highest lift measure.

1. **If** Frequency > 51 **and**
   Duration ≤ 134 **and**
   Degree ≤ 0.001 **and**
   Betweenness > 0.004 **and**
   $0.030 <$ Closeness ≤ 0.032
   then Community A [Lift 4.1]
2. **If** $45 <$ Frequency ≤ 130 **and**

$82 <$ Duration ≤ 109 **and**
$0.0002 <$ Degree ≤ 0.0004 **and**
Betweenness ≤ 0.0002 **and**
Closeness ≤ 0.026
then Community B [Lift 4.9]

3. **If** Degree > 0.002 **and**
Betweenness > 0.01 **and**
Closeness ≤ 0.028
then Community C [Lift 23.9]

4. **If** Frequency ≤ 102 **and**
$0.0012 <$ Degree ≤ 0.0024 **and**
Closeness > 0.026
then Community D [Lift 7.9]

Because the communities are sparse, as is the network itself, the centrality values of the customers pertaining to each community are low. However, there is a clear difference in terms of centrality values between the community that is declining (community B) and the ones that are stagnated or growing. According to rule number 2, community B is comprised of customers with low node centrality. These two facts (Community B declining and showing low centrality values) may be correlated. The community is not overall consistent and 'influence' is not well spread across all people is the community. Communities C and D have reasonable degree centralities, in comparison with the other two communities, probably due to their relative reduced size. Even though community A has better closeness centrality, this measure is similar for all communities. Closeness gives a hint about the topology of the network, *i.e.*, how fast individuals reach all others inside their community. In short, we were able to find rules for the studied communities which, not only outline their profile, but also quantify their distinguishing properties.

5 CONCLUSIONS

From a business point of view, analysing common properties of groups of customers helps to support the decision making of marketeers. Several frameworks have been proposed to study the dynamics of communities in networks. However, these methodologies may not be well suited to deal with large-scale networks, which are typically characterised by a large number of communities. In this paper, we tackle this problem by proposing an integrated and business-oriented framework for selecting a subset of interesting communities, tracking their evolution over time, and characterise their properties in a comprehensible way. A case study using a large-scale network from a telecommunications company showed the applicability and usefulness of the proposed framework. The modularity obtained by the community detection algorithm returned values around 0.90, in all six time-points. This shows that there is a meaningful community structure in the studied network. Based on multiple criteria, we then selected the most interesting communities in the network, from the business perspective. By applying the MECnet framework, we monitored the evolution of those communities. With a monthly interval between each mapping procedure, we verified stability in the comunities over the time span. Although we consider that there is an overall good consistency, the weight of the edges is generally low, which may be related to the communication patterns of the general population. Exploring the profile of communities, we concluded that growing communities are associated with higher activity measures, such as frequency and recency of calls, and an overall transitivity of their individuals. Also, using a decision trees algorithm, we were able to create a general profile of the communities, based on the attributes of the individuals that comprise them. The community detection algorithm is non-deterministic, which makes it difficult to obtain a good understanding of the evolution of communities over time. Nonetheless, the analysis was performed over high-level communities, *i.e.*, the communities located at the top of the hierarchy produced by the Louvain method, which comprise the smaller ones. For future work, one way to better understand the consistency of the large communities over time, would be to 'zoom' into the hierarchy of communities, and to focus the analysis on the smaller core of the large communities. These might be the ones that essentially drive the dynamics of the large communities.

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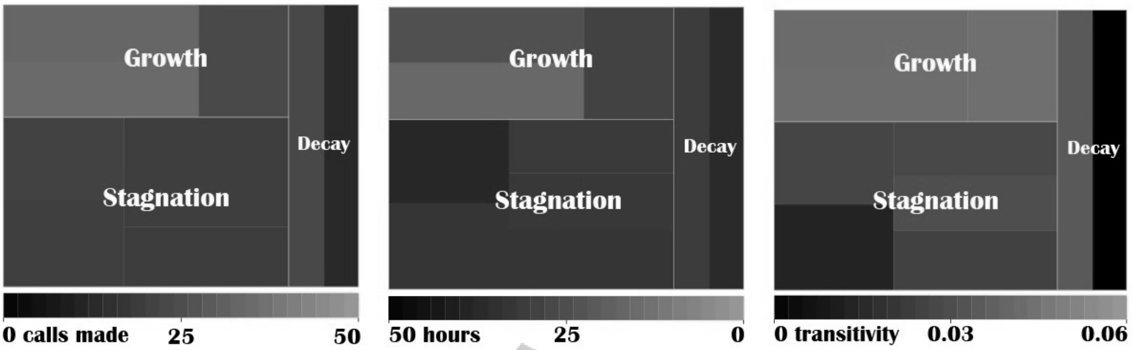

(a) Frequency (b) Recency (c) Transitivity

Figure 4: Relative analysis of the frequency, recency and transitivity values of the selected communities. Each rectangle represents a community. The size of the largest rectangles represent the contribution of each class to the revenue of the company (*i.e.*, the monetary component). Brighter regions indicate higher frequency, lower recency and higher transitivity values.

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