Network Structure and Robustness:
Lessons for Research Programme Design*

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Abstract: The ICT Network of the last two European Research Framework Programmes is deeply influenced by two distinct groups of organizations: a small group of hubs (3% of participants) hold the key in keeping the network together; and a second group of non-hub connectors large enough (39% of participants) with significant share of the overall networking activity to provide a robust base for the network. The ICT Network can survive the removal of single important funding instruments such as integrated projects or specific targeted research projects. Increasing policy rhetoric on innovative application in the next Framework Programme (Horizon 2020) should be reflected in a shift of core participants from largely public research and teaching organizations to private sector companies.

Keywords: Collaborative R&D; innovation; network; Europe; Research Framework Programme; Horizon 2020.

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1. Introduction

Collaboration has become a pillar of the European approach to publicly supported research and technological development. Various forms of research collaboration have defined, more or less, all funding instruments/schemes of the Framework Programme for Research and Technological Development (RTD). The inter-organizational networks that emerge from this funding, together with the networks created through national and regional programmes, provide the core structure of a European Research Area. Still, the inner features of the emergent networks are arguably not adequately understood.\(^1\) The ongoing effort to carefully calibrate Horizon 2020 – the next Framework Programme for RTD – in order to meet Europe’s ambitious objectives requires additional insight.

Naturally, the organizations and individuals that participate in Framework Programmes also participate in other networks, either ‘real’ such as partnerships of various types or interlocking board positions, or ‘virtual’ such as linkages through patents and scientific publications supporting flows of knowledge. That is to say, organizations and individuals are embedded in network layers that together influence their behaviour and performance. Networks bestow an organization with ‘network resources’ (social capital) which, together with the technical and commercial resources, create a major source of strength, innovation and growth. Core organizations in the network (hubs) are assumed to collect extensive benefits from and exert exceptional influence on the network in terms of linkage patterns, partners, and areas of concentration.

This paper presents an empirical analysis of the emergent networks created and maintained by sustained public funding in information and communication technologies

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\(^1\) March 5, 2009 workshop on state-of-the-art network methodologies for evaluating RTD programmes, organized by DG INFSO and DG Research. See Eustace (2009).
(ICTs) through the European Research Framework Programme (FP). We analyze:

- The positioning of European organisations in the ICT-RTD network
- The identification of core organizations (hubs) and their effectiveness in creating and diffusing knowledge
- Network robustness with regards to various funding instruments and different participating organizations

We use social network analysis tools and databases of FP funding and European patent applications to examine the characteristics and performance of the alliance network that has been nurtured during 2002-2008 in the ICT field (ICT-RTD Network). The examined network exhibits the typical bi-polar characteristics of a very large periphery and a small core of very active participating organizations. The ICT-RTD Network was found to be fairly balanced compared to other networks examined previously (such as those built around patent citations), featuring a much smaller proportion of participants in the ultraperipheral category, a significant number of hubs, and a significant number of strong connector organizations (both hubs and non-hubs) which maintain significant number of linkages outside their own module. The ICT-RTD Network appeared to indicate a 3-tier structure in the Framework Programme consisting of the core (highly connected hub organizations), the peripheral organizations, and in the middle a large group of non-hub connector organizations.

All said, the ICT-RTD Network of the past two Framework Programmes is deeply influenced by two distinct groups of organizations: a group of hubs amounting just to 3% of all network participants hold the key in keeping the network together as we know it; and a second group of non-hubs large enough (39% of all participating organizations) and with significant share of the overall networking activity to provide a base for the network. Absent these two groups of organizations, the network collapses. Policy decision makers
and RTD programme managers have been paying attention to the highly connected hub organizations. However, the second important group of organizations with significant connectivity across modules (but rather less within their own modules) has defied policy attention till now (the silent middle). They deserve much more in Horizon 2020.

The ICT-RTD Network is deeply influenced by public research and teaching organizations which play very important roles as hubs and connectors. To the extent that that feature, in turn, influences research orientation and results, RTD network data cannot be easily reconciled with the increasing rhetoric on the innovative application of research results. Greater emphasis on innovation in Horizon 2020 should be reflected in a gradual shift of hubs from public research and teaching organizations to private sector companies.

The ICT-RTD Programmes harness network linkages among large numbers of participants. The resulting network is robust in the sense that its vital signs remain healthy and fairly unchanged with the removal of single important funding instruments. Different instruments, however, play different roles. Whereas Integrated Projects look like the network backbone in terms of the sheer number and the network positioning of organizations and participations they account for, Specific Targeted Research Projects are very important in terms of bringing new participants (more peripheral) into the network. Among the three examined instruments, Networks of Excellence is the least prominent in terms of structural effects onto the network from its removal.

The structure of the paper is as follows. The following second Section describes the data and overviews network topology. Section three analyzes network hubs and examines network effectiveness in producing and diffusing knowledge. Section four looks at network robustness against the main FP funding instruments, on the one hand,
and types of participating organizations on the basis of network positioning, on the other. Finally, Section five summarizes the main findings and discusses policy implications.

2. Data

In this paper, the ICT-RTD Network reflects the linkage between organizations through their participation in the projects funded by the DG INFSO during the Sixth Framework Programme (FP6) (2002-2006) and the first two years of the Seventh Framework Programme (FP7) (2007-2008). The analyzed population consisted of 1,923 collaborative projects and 5,516 unique organizations. Project and participant information was collected from the CORDIS database. The resulting network consists of all dyadic linkages between these organizations as reflected in the analyzed projects.

We used European Patent Office data to construct a separate Patent Citations Network in order to assess the performance of the ICT-RTD network in terms of knowledge production and diffusion. The source was the PATSTAT-KITeS database including all patents and patent citations belonging to the ICT field codes during the period 1990-2010. The first step in creating the Patent Citations Network was to select organizations akin to the ICT RTD technology domains. In doing so, our starting point was the technology-oriented classification, jointly elaborated by Fraunhofer Gesellschaft-ISI (Karlsruhe), Institut National de la Propriété Industrielle (INPI, Paris), and Observatoire des Sciences and des Techniques (OST, Paris). This classification aggregates all IPC codes into 30 technology fields. As far as the selection of technology fields is concerned, we relied on the results of a recent study service carried out for the DG INFSO showing that more than 90% of all patents produced by projects funded by
the DG INFSO are in the fields of Electrical engineering and Scientific Instruments (Optics), as defined by the FhG-OST-INPI classification mentioned above. From the PATSTAT-KITE database we have thus extracted all patents and patent citations corresponding to these IPC codes in the period 1990-2010.

The resulting dataset includes all organizations (1,642, also including the target population of FP ICT-RTD participants) patenting or citing a patent in the selected RTD technological domains. The number of dyadic linkages between organizations citing each other’s patents is 20,606. The Patent Citation Network reflects the linkage between organizations through citations among patents. Patent citations are thought to provide a fairly reliable indicator of “direct” knowledge flows (i.e. spillovers) from the cited to the citing organization (Jaffe and Trajtenberg, 2002).

We constructed the ICT-RTD Network by linking two organizations if they participate in the same one or more ICT RTD project(s). The topological properties of the ICT-RTD Networks are summarized in Table 1. The column FP6+FP7 corresponds to the ICT-RTD Network analysed in this study. The examined network is large: it comprises of 5,516 organizations which participate in 1,923 projects 21,367 times. On average, there are 11.1 organizations participating in a project; moreover, an organization is linked to 43.4 other organizations in this network. A small network density of 0.0079 is typical for a large network like this as is a small value of network betweenness suggesting that linkages among organizations are not concentrated around a particular group of organizations. The small value of the assortativity coefficient implies that local ‘neighborhoods’ of organizations are formed in the network with higher density among

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2 Matlab is used for the network analysis along with the sub-routines provided by Gleich (2008) for the detection of components and Mikail and Sporns (2010) for the hub analysis in the paper.
the included organizations and lesser density with the surrounding area. Despite the large size of the network, participants may reach one another with only a few steps (2.56 on average). Finally, the network exhibits the characteristics of ‘small-worlds’ (Watts, 1999) which theory views as an efficient network structure in transmitting and sharing information (Cowan and Jonard, 2003).³

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Table 1 about here
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3. Analysis of Network Hubs

A very important dimension of the position of an organization (node) in a network relates to the notion of network hub. Informally, a hub may be defined as a node with a very large number of links or, alternatively, as a node that is highly influential by playing the role of network connector, i.e. one connecting nodes that would otherwise remain unconnected. The existence and importance of such hubs in real-world networks has been pointed out by Barabási and Bonabeau (2003) who showed that the linkage distribution tends to be highly skewed: the vast majority of nodes in a network are connected to just one or very few other nodes, whereas a small number of nodes maintains a disproportionately large number of links. The most important consequence of the presence of such network hubs is that the overall connectivity of the network as well as

³ The characteristic path length (2.56) of the ICT-RTD Network is close to the value (2.29) of a corresponding random network while its clustering coefficient (0.833) is quite larger than the value (0.008) of the corresponding random network.
its topological properties crucially depends on few important organizations. Such scale-free networks are vulnerable to the targeted removal of the most important nodes thereby decreasing the ability of the remaining nodes to interact with each other.

Hubs therefore have an extremely important role in partnership networks in terms of contributing in the production and dissemination of knowledge across the network. This Section identifies network hubs in the network, characterizes their attributes, and assesses their effectiveness in producing and diffusing knowledge.

### 3.1. Identification of network hub organizations

A network may be divided into communities (or neighborhoods), based on a similarity metric. An example of a well known such approach is hierarchical clustering where similarly connected nodes are grouped into communities which are then further grouped together with other communities. The process is repeated until the structure of a network is shown as a hierarchical dendrogram (Newman, 2010, pp.386-391). However, in real world, it is difficult to justify the underlying assumption that each organization is a member of exactly one community. It is, instead, more reasonable to assume an organization to possess fractional membership in several communities. Some organizations, for example, may be strongly embedded in one community while others may be positioned between communities in a network. We follow a methodology proposed by Guimerà and Amaral (2005a), which allows such fuzziness in nodes’ community membership by classifying network nodes in a number of ‘system independent’ universal roles based on their connectivity. The first step is to identify
network modules\(^4\) referring to distinct communities of highly interconnected organizations. Specifically, nodes are divided into modules such that the modularity \(M\) of the network is maximized, where \(M\) is defined as

\[
M \equiv \sum_{s=1}^{N_M} \left[ \frac{l_s}{L} - \left( \frac{d_s}{2L} \right)^2 \right]
\]

In the above equation, \(N_M\) is the number of modules, \(L\) is the number of links in the network, \(l_s\) is the number of links between nodes in module \(s\), and \(d_s\) is the sum of the degrees of the nodes in module \(s\). \(N_M\) is not set to a specific value in advance; rather it is determined by the network. \(M\) takes a value between 0 and 1. It is equal to 0 when there is no meaningful structure. Networks with larger \(M\) feature strong structure.\(^5\) The ICT-RTD network has modularity value larger than 0.3, suggesting a strong modular structure, and is made up with 18 modules, of which five largest modules keep 81% of nodes in the network.\(^6\)

After module-partitioning, network nodes are classified according to the role they play within and between modules. In particular, Guimerà and Amaral (2005a) proposed a classification of nodes based on two measures: within-module degree and participation coefficient. \textit{Within-module degree} measures how well connected a node is to other nodes within its module. It is defined by:

\[
\zeta_i = \frac{k_i - \bar{k}_i}{\sigma_{k_i}}
\]

\(^4\) We use the terminology ‘module’ instead of ‘community’ or ‘cluster’ hereafter, following Guimerà and Amaral’s (2005a) terminology.

\(^5\) In practice, the modularity of strongly-structured networks falls in the range between 0.3 and 0.7 (Newman and Girvan, 2004). Examples of networks with strong modularity structure include the air transportation network (Guimerà, Mossa, Turtschi and Amaral, 2005), the Internet (Pastor-Satorras, Vázquez and Vespignani, 2001), and metabolic networks (Guimerà and Amaral, 2005b).

\(^6\) Indicatively, the top five modules in the ICT-RTD network have 1,142, 980, 940, 728, and 666 nodes respectively.
where $k_i$ is the number of links of node $i$ to other nodes in its module $s_i$, $\bar{k}_{s_i}$ is the average of $k_i$ over all the nodes in $s_i$, and $\sigma_{k_i}$ is the standard deviation of $k_i$ in $s_i$. According to Guimerà and Amaral (2005a), nodes with $z \geq 2.5$ can be classified as module hubs and nodes with $z < 2.5$ as non-hubs. In other words, a node with a significantly larger than average number of links to other nodes in its own module is defined as a module hub, whereas a node with an average (or lower) number of links is defined as a non-hub.

The participation coefficient captures the extent to which a node is connected to other nodes outside its own module. It is defined by:

$$P_i = 1 - \sum_{s=1}^{N} \left( \frac{k_{is}}{k_i} \right)^2$$

where $k_{is}$ is the number of links of node $i$ to nodes in module $s$, and $k_i$ is the total number of links of node $i$. The participation coefficient of a node is therefore close to one if its links are uniformly distributed among all the modules and close to zero if all its links are within its own module.

Hub and non-hub nodes are further divided into sub-groups, respectively, by the value of participation coefficient.\footnote{We follow Guimerà and Amaral (2005a) and select the limit values for participation coefficient.} The combination of these two measures yields a partition of nodes into seven categories (or roles), four related to non-hub nodes and three to hub nodes:

**Non-hub nodes ($z < 2.5$)**

- **Ultra-peripheral nodes** (Role 1): Node has all its links within its module ($P \approx 0$).
- **Peripheral nodes** (Role 2): Node has a small positive participation coefficient.
(P<0.625), i.e. it has a large fraction of all its links within its module.

- **Non-hub connectors** (Role 3): Node has a fairly large participation coefficient (0.625<P<0.8), i.e. it has a large fraction of its links to other nodes in other modules.

- **Non-hub kinless nodes** (Role 4): Node has a large participation coefficient (P>0.8), i.e. it has very few links to nodes in its own module; it cannot be clearly assigned to any single module.

  **Hub nodes** (z ≥ 2.5)

- **Provincial hubs** (Role 5): Node with a large degree has at least 5/6 of its links within its module (P≈0.3).

- **Connector hubs** (Role 6): Node with a large degree has at least half of its links within its module (P<0.75).

- **Kinless hubs** (Role 7): Node with a large degree has fewer than half of its links to nodes within its module (P>0.75), so that it may not be clearly associated to a single module.

Figure 1 provides a visual illustration of this type of partition. The role partition of nodes in the ICT-RTD network according to this taxonomy is shown in Table 2. Indicatively, organizations categorized as ultra-peripheral nodes (Role 1) or Peripheral nodes (Role 2) have small numbers of linkages to other organizations both within and outside their own module. They are likely to be just peripheral organizations or specialists of some technological domains. In contrast, organizations categorized as connector hubs (Role 6) or kinless hubs (Role 7) have relatively large numbers of linkages to other organizations both within their module and across modules. They are likely to be very actively engaged in multiple projects. Organizations categorized as
provincial hubs (Role 5) have relatively more linkages to other organizations within their own modules than those to other modules. These can be occasional project coordinators that coordinate a project or two but not much else.\textsuperscript{8} Finally, organizations categorized as non-hub connectors (Role 3) or non-hub kinless nodes (Role 4) have more linkages to other modules than linkages within their own modules. They are likely to be engaged in multiple projects (but not as actively as those in Roles 6 & 7).

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Figure 1 and Table 2 about here
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Several important observations are in order. First, the ICT-RTD network is a typical scale-free network (Barabási and Albert, 1999): the large majority of participants live in the periphery whereas a small proportion of them are highly connected. Second, the network distributes organizations across all seven categories. Third, whereas 58\% of all network participants are in the peripheral and ultraperipheral categories (Roles 1-2), a very significant share (about 40\%) in the non-hub connector and kinless non-hub categories (Roles 3-4) are not highly connected within their own modules but well connected across modules. A further 3\% in the connector hub and kinless hub categories (Roles 6-7) are very highly linked within and across modules. Fourth, about half of the hub organizations in this network are kinless hubs meaning that even though they are hubs in their respective modules fewer than half of their total links are to nodes within

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\textsuperscript{8} The five organizations categorized as provincial hubs (Role 5) in Table 2 include two regional governments, two engineering consultancies, and one accounting firm.
these modules. Fifth, significant numbers of nodes in Roles 3-4 and 6-7 in the ICT-RTD Network imply that a significant portion of participating organizations, both hubs and non-hubs in their modules, are ‘nomadic’ – that is, they venture beyond their narrow worlds to meet new kinds of partners.

The above observations suggest a 3-tier structure of the examined ICT-RTD Network consisting of the core highly connected, ‘highly nomadic’ hubs (corresponding to Roles 6-7), the middle non-hub but ‘nomadic’ connectors (Roles 3-4), and the periphery (Roles 1-2).

Table 3 shows the distribution of nodes by organizational type (industry, university, public research institute, other) in the ICT-RTD Network. Notice that the university share in hub nodes is disproportionately large: a whopping 52% of all hubs are universities. If we add another 4% of hubs represented by public research institutes and another 14% by other organizations (typically public authorities) we get 70% of hubs in this network being non-industry.

The ICT-RTD network thus appears to be deeply influenced by universities and public research institutes. To the extent that the organizational type of network core participants influences the research orientation of the network, recent network participation data cannot be easily reconciled with the increasing rhetoric with regards to
the Framework Programme promoting the innovative application of research results. This is not to say that the Programme is not useful or that it is wrongly focused. In fact, since its inception the Programme has been considered an instrument to promote pre-competitive research. It is in more recent years that emphasis in the political realm has gradually shifted towards application and innovation. If that is so, then it may not be adequately reflected in the composition of research networks.

3.2. **Hub effectiveness in producing and diffusing knowledge**

Hubs are expected to play an important role in producing and diffusing knowledge. We assess the extent to which they effectively work as a source of information and ideas for other organizations and/or as knowledge depositories. To this purpose, we exploit the available patent data to derive various indicators of knowledge creation and diffusion. We use the following three indicators to capture the effectiveness of organizations in creating new knowledge:

- **Number of patents**: Number of patents in the relevant technology fields.
- **Number of citations received** (weighted): Number of citations received by the patents of an organization divided by the total number of patents of that organization. It is a measure of quality of the patent portfolio of an organization.
- **Number of highly cited patents**: Number of frequently cited patents. It is a measure of importance of the patent portfolio of an organization.

An important channel of knowledge transfer is represented by the disembodied flow of scientific and technical information, i.e. knowledge spillovers. Information contained in patent citation patterns can be used to assess the effectiveness of an
organization in disseminating knowledge. In order to measure the effectiveness in diffusing knowledge, we use the following two indicators:

- **Degree Centrality in the Patent Citation Network**: Number of direct connections of a node (organization). Nodes with the highest degree are the most active in the sense that they have the most ties to other actors in the network.

- **Betweenness Centrality in the Patent Citation Network**: A node is central if it lies between many pairs of other nodes not directly connected between them. A node with high betweenness centrality has great influence over knowledge flows in the network.

To the extent that hubs are an important source of knowledge for other organizations, one would expect that they would capture a substantial fraction of all citations and that they are cited by a large number of citing organizations. The results for four categories of participants in the ICT-RTD Network\(^9\), including the hub nodes (Roles 5-7) and the kinless non-hubs (Role 4) in which nodes have many links to nodes across modules, are shown in Table 4.

\[\begin{array}{|c|c|c|c|}
\hline
\text{Category} & \text{Production} & \text{Dissemination} \\
\hline
\text{Hubs} & 0.8 & 0.6 \\
\text{Non-Hubs} & 0.4 & 0.3 \\
\end{array}\]

It can be observed that the highly ‘nomadic’ kinless hubs (Role 7) perform, on average, at a level of magnitude above other organizations. They are much more effective in terms of both production and dissemination of knowledge. At some distance they are

\(^9\) We conducted a series of ANOVA to test for differences among categories (Roles 1-7) for all effectiveness indicators to verify that these categories were significantly different from one another. For all indicators, F-values ranged between 21.09 and 85.8 with p-values < 0.0001.
followed by connector hubs (Role 6) corresponding to organizations that are hubs in their modules but also keep a significant part of linkages outside the module. Again at some distance, kinless non-hubs (Role 4) come third. They correspond to organizations that are not hubs in their own modules but maintain a very large proportion of their linkages outside the module. Connector provincial hubs (Role 5) come dead last. They correspond to organizations that are hubs in their respective modules and keep the vast majority of linkages within module.

A proposition to pay attention to kinless hubs (Role 7) and to connector hubs (Role 6) on the basis of this performance would not be surprising. Neither would it be new. These organizations perform better than others in terms of both production and dissemination of knowledge. They are also ‘highly nomadic’, meaning that they create linkages across modules. An interesting category, we believe, is the kinless non-hub organizations (Role 4), which in the Framework Programmes appear to be a significant group, and different from the other two categories that experts have focused on until now, i.e., the core hubs and the peripheral organizations10.

4. ICT-RTD Network Robustness

4.1. Network robustness vis-à-vis funding instruments

We assess the importance of the different funding instruments (Integrated Projects (IPs), Specific Targeted Research Projects (STRePs), and Networks of Excellence (NoEs)) in determining the topological properties of the ICT-RTD Network. To accomplish this, we conduct a sensitivity analysis, which consists of removing from the

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10 Kinless non-hubs (Role 4) and non-hub connectors (Role 3) together make up almost 40% of the body of participants (Table 2).
focal network all projects (and related organizations) funded according to specific measures and instruments and observe the impact of such removal on the major topological properties of the network. The implicit argument is that the more sensitive the topology of the network is to the removal of instrument-specific projects, the more important the instrument under examination is to the network.

IPs, STRePs and NoEs are designed to serve different policy goals. IPs purport to increase Europe’s competitiveness or to address major societal needs by assembling the necessary critical mass for a targeted field of research. They are large in size and usually include several components. Their research activities may cover the whole research spectrum from basic to applied research. NoEs purport to strengthen scientific and technological excellence on a particular research topic by integrating the critical mass of resources and expertise. They are relatively small in terms of funding and concentrate primarily on networking of the players in a field. STRePs deal with narrowly defined research. They are small in size and focus on a single issue.

In FP7, European Commission consolidated the IP and STReP categories into Collaborative Projects (CPs). For our needs here, in order to aggregate across the two FPs, we decomposed the CP category: projects with 11 or more participants were classified as IPs whereas those with 10 or fewer were classified as STRePs\textsuperscript{11}. Table 5 shows the distribution of FP projects after regrouping.

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{IPs} & \textbf{STRePs} \\
\hline
\hline
11 & 10 \hline
\end{tabular}
\caption{Distribution of FP projects after regrouping}
\end{table}

\textsuperscript{11} The 10/11 threshold was chosen based on the distribution pattern of projects in FP6 where IPs have had an average of 19.7 participants (standard deviation 9.54) and STRePs have had an average of 8.4 participants (standard deviation 2.79).
Table 6 shows the results of the sensitivity analysis for the ICT-RTD Network\textsuperscript{12}. The column “All” indicates the values of the cumulative network of all project participants – i.e., including all funding instruments – similar to the corresponding column in Table 1. The remaining columns are the results of sensitivity analysis. For instance, the column “No IP” shows the topological properties of the ICT-RTD Network without IP projects. Similarly for “No STReP” and “No NoE”.

The removal of IPs results in the loss of almost 1/3 (30\%) of the nodes (participating organizations) and almost half (47\%) of the edges (links). While this effect is in itself quite significant – loss of about 2/5 of the overall program participations – network topology does not change dramatically. The network appears fairly robust in the removal of such a big chunk of activity. Still, the fact that thirty percent of organizations in the network only participate in IP-funded projects indicates that this instrument captures many organizations that otherwise would not participate into the Framework Programme.

The removal of STRePs results in the loss of 2/5 (41\%) of the nodes (participating organizations), almost one quarter (23\%) of the edges (links), and half of all network participations. These numbers suggest that STReP-funded projects account for many of the peripheral participants of the network. This is further corroborated by the fact that the removal of STRePs results in a very significant increase in network density whereas it leaves the other vital network characteristics more or less unchanged. The STReP

\textsuperscript{12} We also divided the samples to those corresponding to FP6 and FP7 projects and ran the sensitivity analysis separately in order to check the validity of the joint programme analysis reported here. The network topological properties remain quite similar – apart from network size (i.e. number of nodes, number of links).
instrument, then, is the primary means through which new organizations are brought into the network. Many of these organizations play a peripheral role, which is not an evaluation of their quality but rather of their frequency of participation.

The removal of NoEs from the network results in the loss of 4% of the nodes (participating organizations) and 1/5 of the edges (links), with a total loss of about 1/10 of total participations. The ICT-RTD Network remains robust: its topological properties do not change markedly. NoEs were purported to add another strong layer and thus strengthen the European research network. The contribution of this instrument in the structure of the network is, however, not obvious in these numbers. The instrument does not seem to bring large numbers of new participants which otherwise would not have participated in the Framework Programme.

Overall, observation of the network characteristics suggests that organizations participate in multiple projects across different programs repeatedly. The ICT-RTD Network is cohesive. All nodes belong to the same component and remain there after the removal of individual funding instruments. Different instruments, however, play different roles. Whereas IPs look like the backbone in terms of the sheer number of participations and their network location, STRePs are very important in terms of bringing new participants into the network. Among the three examined instruments, NoEs is the least prominent in terms of structural effects onto the network as a result of its removal.

We also perform an additional sensitivity analysis to examine how the removal of different instruments influences the network in terms of distribution of roles. Results are summarized in Table 7. In the first column “All” corresponds to the original IST-RTD Network – i.e., including all funding instruments – same as Table 1. The remaining rows
are the results of sensitivity analysis. For instance, the row “No IP” shows the topological properties of the ICT-RTD Network without IP projects. Similarly for “No STReP” and “No NoE”.

The removal of IPs results in a steep drop of connector hubs (Role 6) (decrease by two thirds), elimination of the provincial hubs (Role 5) and serious decreases of non-hub connectors (Role 3) and peripheral nodes (Role 2). Removal of NoEs does not change much besides a redistribution of roles in the connector hubs (Role 6) (a quarter drop) and kinless non-hub (Role 4) (increase by three quarters). Removal of STRePs results in very significant decreases across all categories, both hub and non-hub organizations.

Consistent with the prior sensitivity analyses in this Section, NoEs appear to be the least influential funding instrument across all networks. The story is different for IPs and STRePs. Removal or either IPs or STRePs results into deep cuts in terms of participating organizations (nodes). If anything, the influence of IPs is extensive but somewhat more concentrated in terms of node categories compared to the influence of STRePs which comes across all categories.

4.2. Network robustness vis-à-vis participant category

How important are different types of network participants in determining the core topological characteristics of the ICT-RTD Network? The question has policy interest
because hub nodes are typically viewed as the backbone of the network, keeping the pieces together. To answer this question we performed sensitivity analysis of the network by gradually removing groups of participating organizations in the different node categories of Figure 1. Results are reported in Table 8. This Table should be read as follows: the column “Roles 1-7” corresponds to the original cumulative ICT-RTD Network – column marked “All” in Table 6 and the corresponding column in Table 1. The next column “Roles 1-6” shows the topological properties of the ICT-RTD Network without kinless hubs (Role 7). The next column “Roles 1-5” shows the topological properties of the ICT-RTD Network without connector hubs and kinless hubs (Roles 6-7). And so forth.

Table 8 about here

The first observation is the huge effect of a small number of organizations in a single category: 86 kinless hubs (Role 7) (out of a total 5,516 organizations, or 1.6%) account for 38% of all linkages in the network. When kinless hubs are removed, the number of network components rises from 1 to 7 and the core characteristics of the network are deeply affected. The assortativity coefficient – measuring the tendency of nodes to link to other nodes with similar degree – turns from negative to positive suggesting that kinless hubs are distinct from other organizations. Network betweenness becomes much smaller (one-third), suggesting that network linkages are extensively
concentrated on kinless hubs. In short, kinless hubs are of critical importance in maintaining the overall connectivity of the ICT-RTD Network.

The next group of network participants, 74 connector hubs (Role 6), has the next most important influence on the ICT-RTD Network. Their elimination results yet in another very serious cut of links (edges), decrease in average degree, increase in the assortativity coefficient, and more than doubling of the network components. Interestingly, though, the characteristics within the largest component remain more or less the same.

The network remains fairly stable with the removal of the few provincial hubs (Role 5). Similarly with the removal of 173 kinless non-hubs (Role 4), save for a large jump in the number of components.

The next major change in the ICT-RTD Network comes with the removal of non-hub connectors (2,074 organizations, Role 3). The network essentially breaks down then with the jump of the number of components from 30 to 223. All other vital characteristics of the network also change dramatically. There is little, if any, of network left with only participating organizations in Roles 1-2 (accounting for more than half of total network participants).

Strongly suspected before and emphatically shown herein, the ICT-RTD Network of the last two Framework Programmes is deeply influenced by a small number of organizations. Two groups of hub organizations (Roles 6-7) amounting to just 3% of all network participants hold the key in keeping the network together. Interestingly, however, it is a third group of non-hub organizations (Role 3) that is large enough (38% of all participating organizations) and with significant share of activity (linkages) to provide a
base for the network. Absent these three groups of organizations, the network collapses into more than 200 unconnected sub-networks; knowledge flow among is disrupted. They deserve significant attention by policy decision makers in view of Horizon 2020.

5. Conclusion

The method of Guimerà and Amaral (2005a) was employed to classify network participants into seven categories on the basis of their connectivity within their own modules (‘neighbourhoods’) and across modules. *Within module degree* distinguished hubs from non-hubs. Four non-hub categories (ultraperipheral nodes, peripheral nodes, non-hub connectors, kinless non-hubs) involve organizations loosely connected to others in their own module. The remaining three hub categories (kinless hubs, connector hubs, and provincial hubs) involve organizations with much higher connectivity to others in their own module. *Participation coefficient* distinguished cross-module strong connectors from weak connector organizations. Three weak connector categories (ultraperipheral nodes, peripheral nodes, provincial hubs) exhibit very low connectivity across modules. The remaining four strong connector categories (non-hub connectors, kinless non-hubs, connector hubs, and kinless hubs) exhibit much higher connectivity across modules. Kinless hubs (Role 7) stand out since they exhibit the highest levels of connectivity both within their own module and across modules.

Not surprisingly, the ICT-RTD Network of collaborative projects formed through the Framework Programmes was characterized as free scale, with the typical bi-polar characteristics of a very large periphery and a small core of very active participating organizations. The network featured a significant number of hubs and a significant
number of ‘nomadic’ hub and non-hub organizations which link extensively outside their own module. In fact, the ICT-RTD Network appeared to indicate a 3-tier structure in the Framework Programme consisting of (i) a core of highly connected hub organizations on the one extreme, (ii) a large important group of non-hub connector organizations in the middle, and (iii) the peripheral organizations. It is this middle group of strong non-hub connectors that prior studies and policy decision makers have tended to miss until now.

Who are these middle-level ‘nomads’? A first look indicates no obvious common characteristics. They include all sorts of organizations, large and small, university and industry and research institutes, located across Europe and beyond. Examples include Zenon Robotics and Informatics (Greece), the University of Ljubljana (Slovenia), Microsoft (US), the University of Bremen (Germany), Oracle Corporation (US), TTI Norte (Estonia), Deutsche Welle (Germany), Exalead (France), Asea Brown Boveri (Switzerland), Deloitte Conseil (France), Itricity (Netherlands), Ydreams-Informatica (Portugal), and Sweden Connectivity AB (Sweden).

Hints for an explanation may be found in the debate over network structure optimality (Gilsing et al., 2007; Vonortas, 2009). The argument for network structure optimality is about balancing the incentive to lower the operating cost in a network by facilitating information exchange and decreasing relational risk versus the incentive of profit opportunities by breaking new ground to bridge isolated regions of relationships in the network. This ‘entrepreneurial’ activity corresponds to the selective establishment of information-rich ties across ‘structural holes’ in the network (Burt, 1992) and confers powerful brokerage positions and significant rents. This contrasts with the style of networking involved in Coleman’s (1988) argument for dense network structures based
on solid amounts of social capital. Here, redundant ties among firms resolve collective action problems and improve coordination. The rent accrues to the group and is allocated among its members on the basis of relative market power and adjudication rules.

The two styles of networking can be complementary, providing different advantages to, and being used for different purposes by, firms and other actors. The question of appropriate balance will, at least in part, depend on whether the predominant mode of operation in a sector concentrates on the better exploitation of existing technologies, skills, and information, or the exploration of emerging innovations and other changes (March, 1991). It is reasonable to anticipate that both processes are often needed, pursued simultaneously, and compete for limited resources within individual organizations (March, 1991). The type and optimal amount of social capital for an organization to maintain will change in accordance with the distinct strategic mixtures of exploitation and exploration pursued by that organization in different environments (Nooteboom and Gilsing, 2004; Rowley et al., 2000).

One can argue that what we are observing in this paper is this interplay where network participants find it advantageous to create strong social capital within a module as well as try to connect cross modules. The ICT sector is certainly wide enough to involve business areas where the predominant mode of operation is exploration and others where knowledge exploitation prevails. If a ‘business area’ roughly corresponds to a ‘module’ in our analysis, we have a hypothesis for research: cross-module connectors are entrepreneurial participants who create value by connecting across research areas. The result of such an investigation would seem to us to have significant policy and strategy implications.
Policy decision makers and RTD programme managers must, of course, pay attention to highly connected hub organizations like our kinless hubs (Role 7) and connector hubs (Role 6). Kinless hubs perform better than others in terms of both production and dissemination of knowledge. They are also highly ‘nomadic’, meaning that they create large numbers of linkages across modules. Connector hubs (Role 6) follow close in terms of performance and connectivity. It is the third important group of organizations with significant connectivity across modules (but rather less within their own modules) which have defied policy attention till now (the silent middle). We believe the designers of Horizon 2020 may want to pay attention to this latter group.

All said, the paper puts forward a number of findings. First, the ICT-RTD Network of the past two Framework Programmes is deeply influenced by two distinct groups of organizations: a group of hubs made up of kinless hubs and connector hubs (Roles 6-7) amounting just to 3% of all network participants hold the key in keeping the network together as we know it; and a second group of non-hubs made up of kinless non-hubs and non-hub connectors (Roles 3-4) large enough (39% of all participating organizations) and with significant share of the overall networking activity to provide a base for the network. Absent these two groups of organizations, the network collapses.

Second, the ICT-RTD Network is deeply influenced by public research and teaching organizations which play very important roles as hubs and connectors. To the extent that that in turn influences research orientation and results, and to the extent that innovation is not the primary strength of universities and public research institutes, network data cannot be easily reconciled with the increasing rhetoric on innovative application. Greater emphasis on innovation in Horizon 2020 should be reflected in a
shift of hubs from public research and teaching organizations to private sector companies.

Third, the ICT-RTD Programmes harness network linkages among a large number of participants. The resulting network is robust in the sense that its vital signs remain healthy and fairly unchanged with the removal of single most important funding instruments. Different instruments, however, play different roles. Whereas IPs look like the network backbone in terms of the sheer number and network positioning of organizations and participations they account for, STRePs are very important in terms of bringing new participants (more peripheral) into the network. Among the three examined instruments, NoEs are the least prominent in terms of structural effects onto the network from their removal.

We close with suggestions for future research. The preceding discussion makes it clear that the important characteristic cutting across the two groups of organizations sustaining the ICT-RTD Network – kinless and connector hubs, on one hand, and kinless and connector non-hubs, on the other – is not their hub positioning within their own modules but their ‘nomadic’ tendencies in terms of building strong connections across modules. It is, we believe, this feature that future policy-oriented social network analysis must examine in more detail. Connected to this is a more accurate understanding of the meaning of a module (neighbourhood) in different contextual environments. Better understanding of both of these features will make both the design of the new European Research Framework Programme (Horizon 2020) and its evaluation more effective.
References


27
Organizational Science, 2(1): 71-87.
Table 1: Topological Properties of the ICT-RTD Network

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of projects</td>
<td>1,923</td>
<td>984</td>
<td>939</td>
<td></td>
</tr>
<tr>
<td>Number of participants</td>
<td>21,367</td>
<td>12,578</td>
<td>8,789</td>
<td></td>
</tr>
<tr>
<td>Average number of participants per project</td>
<td>11.1113</td>
<td>12.7825</td>
<td>9.3600</td>
<td></td>
</tr>
<tr>
<td>Number of nodes</td>
<td>5,516</td>
<td>3,977</td>
<td>2,828</td>
<td></td>
</tr>
<tr>
<td>Number of edges</td>
<td>119,663</td>
<td>90,515</td>
<td>39,725</td>
<td></td>
</tr>
<tr>
<td>Average degree</td>
<td>43.3876</td>
<td>45.5192</td>
<td>28.0941</td>
<td></td>
</tr>
<tr>
<td>Network density</td>
<td>0.0079</td>
<td>0.0114</td>
<td>0.0099</td>
<td></td>
</tr>
<tr>
<td>Network betweenness</td>
<td>0.1464</td>
<td>0.152</td>
<td>0.1467</td>
<td></td>
</tr>
<tr>
<td>Assortativity coefficient</td>
<td>-0.1330</td>
<td>-0.1149</td>
<td>-0.0920</td>
<td></td>
</tr>
<tr>
<td>Network diameter</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Characteristic path length</td>
<td>2.5556</td>
<td>2.5156</td>
<td>2.637</td>
<td></td>
</tr>
<tr>
<td>Clustering coefficient</td>
<td>0.8334</td>
<td>0.8462</td>
<td>0.8128</td>
<td></td>
</tr>
</tbody>
</table>

(In all three periods, all nodes are directly or indirectly connected with one another, respectively. That is, each ICT-RTD Network consists of one component.)

*Node:* Unique organizations in network  
*Edge:* Connection between nodes  
*Average degree:* Average number of other nodes which a node is directly connected to  
*Network density:* Ratio of actual connections over the maximum number of possible connections  
*Network betweenness:* Index measuring the extent to which particular nodes lie ‘between’ other organizations in the network. Higher values suggest network connection is concentrated on a certain group of organizations  
*Assortativity coefficient:* Index measuring organizations’ tendency to connect to other organizations with similar degree. Positive values suggest organizations connect to their kin (max value 1).  
*Network diameter:* Largest number of connections separating two organizations  
*Characteristic path length:* Median of average number of connections separating two organizations  
*Clustering coefficient:* Index indicating the extent to which the organizations connected to a given organization tend to also be connected to each other
### Table 2: Participating Organizations (Nodes) Distribution by Role (ICT-RTD Network)

<table>
<thead>
<tr>
<th>Hub roles</th>
<th>Non-hub nodes</th>
<th>Hub nodes</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Role 1</td>
<td>Role 2</td>
<td>Role 3</td>
</tr>
<tr>
<td>Ultraperipheral nodes</td>
<td>142</td>
<td>3,049</td>
<td>1,997</td>
</tr>
<tr>
<td>Peripheral nodes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-hub connector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinless non-hub</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provincial hubs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connector hubs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinless hubs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of nodes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: Network Participant (Node) Distribution by Organizational Type (ICT-RTD Network)

<table>
<thead>
<tr>
<th>Organization type</th>
<th>Number of organizations (share, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In the ICT-RTD Network</td>
</tr>
<tr>
<td>Universities</td>
<td>876 (15.88)</td>
</tr>
<tr>
<td>Industry</td>
<td>3,351 (60.76)</td>
</tr>
<tr>
<td>Public research institute</td>
<td>724 (13.13)</td>
</tr>
<tr>
<td>Others*</td>
<td>565 (10.24)</td>
</tr>
<tr>
<td>Total (%)</td>
<td>5,516 (100)</td>
</tr>
</tbody>
</table>

*Others include institutions such as public authorities, foundations, non-governmental and unidentified organizations.

---

13 We also calculated this distribution for the ICT-RTD Networks of FP6 and FP7 separately and found similar distribution with the aggregate network presented here.
<table>
<thead>
<tr>
<th>Effectiveness indicator (average over organization)*</th>
<th>Role 4</th>
<th>Role 5</th>
<th>Role 6</th>
<th>Role 7</th>
<th>Overall average for nodes in Roles 4-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree centrality</td>
<td>7.08</td>
<td>1.80</td>
<td>29.00</td>
<td>59.71</td>
<td>25.45</td>
</tr>
<tr>
<td></td>
<td>(29.62)</td>
<td>(2.49)</td>
<td>(59.14)</td>
<td>(107.87)</td>
<td>(68.40)</td>
</tr>
<tr>
<td>Betweenness centrality (x 0.001)</td>
<td>0.35</td>
<td>0.24</td>
<td>1.78</td>
<td>5.61</td>
<td>2.03</td>
</tr>
<tr>
<td></td>
<td>(2.01)</td>
<td>(0.53)</td>
<td>(5.62)</td>
<td>(14.58)</td>
<td>(8.27)</td>
</tr>
<tr>
<td>Number of citations/patent received</td>
<td>0.225</td>
<td>0.600</td>
<td>0.418</td>
<td>0.543</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>(0.65)</td>
<td>(1.34)</td>
<td>(0.53)</td>
<td>(0.57)</td>
<td>(0.63)</td>
</tr>
<tr>
<td>Number of patents</td>
<td>153.65</td>
<td>3.20</td>
<td>860.29</td>
<td>2,954.41</td>
<td>1,032.28</td>
</tr>
<tr>
<td></td>
<td>(900.73)</td>
<td>(5.07)</td>
<td>(4,032.82)</td>
<td>(10,936.57)</td>
<td>(6,003.39)</td>
</tr>
<tr>
<td>Number of highly-cited patents</td>
<td>2.28</td>
<td>0</td>
<td>21.46</td>
<td>58.78</td>
<td>21.09</td>
</tr>
<tr>
<td></td>
<td>(12.96)</td>
<td>(0)</td>
<td>(110.97)</td>
<td>(238.95)</td>
<td>(134.09)</td>
</tr>
</tbody>
</table>

*Standard deviation in parentheses.
### Table 5: Distribution of FP Projects by Funding Instrument after Regrouping

<table>
<thead>
<tr>
<th>Framework Programme</th>
<th>Funding Instrument*</th>
<th>IP</th>
<th>STReP</th>
<th>CP</th>
<th>NoE</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP6</td>
<td></td>
<td>253</td>
<td>669</td>
<td>n/a</td>
<td>62</td>
<td>984</td>
</tr>
<tr>
<td>FP7</td>
<td></td>
<td>221</td>
<td>687</td>
<td>908</td>
<td>31</td>
<td>939</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>474</td>
<td>1,356</td>
<td>908</td>
<td>93</td>
<td>1,923</td>
</tr>
</tbody>
</table>


### Table 6: Topological Properties of the ICT-RTD Network (sensitivity analysis)

<table>
<thead>
<tr>
<th>Topological property</th>
<th>All</th>
<th>No IP</th>
<th>No STReP</th>
<th>No NoE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of projects</td>
<td>1,923</td>
<td>1,449</td>
<td>567</td>
<td>1,830</td>
</tr>
<tr>
<td>Number of participants</td>
<td>21,367</td>
<td>13,047</td>
<td>10,806</td>
<td>18,881</td>
</tr>
<tr>
<td>Average number of participants per project</td>
<td>11.1113</td>
<td>9.0041</td>
<td>19.0582</td>
<td>10.3175</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>5,516</td>
<td>3,852</td>
<td>3,269</td>
<td>5,320</td>
</tr>
<tr>
<td>Number of edges</td>
<td>119,663</td>
<td>63,503</td>
<td>92,566</td>
<td>94,230</td>
</tr>
<tr>
<td>Average degree</td>
<td>43.3876</td>
<td>32.9714</td>
<td>56.6326</td>
<td>35.4248</td>
</tr>
<tr>
<td>Network density</td>
<td>0.0079</td>
<td>0.0086</td>
<td>0.0173</td>
<td>0.0067</td>
</tr>
<tr>
<td>Network betweenness</td>
<td>0.1464</td>
<td>0.1516</td>
<td>0.1356</td>
<td>0.1601</td>
</tr>
<tr>
<td>Assortativity coefficient</td>
<td>-0.1330</td>
<td>-0.0948</td>
<td>-0.1278</td>
<td>-0.1198</td>
</tr>
<tr>
<td>Network diameter</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Characteristic path length</td>
<td>2.5556</td>
<td>2.6836</td>
<td>2.3339</td>
<td>2.6023</td>
</tr>
<tr>
<td>Clustering coefficient</td>
<td>0.8334</td>
<td>0.8349</td>
<td>0.8343</td>
<td>0.8249</td>
</tr>
</tbody>
</table>

(In all networks, all nodes are directly or indirectly connected with one another, respectively. That is, each network consists of one component.)
### Table 7: Participating Organizations (Nodes) Distribution by Role in the Network (sensitivity analysis)

<table>
<thead>
<tr>
<th>Network</th>
<th>Role 1</th>
<th>Role 2</th>
<th>Role 3</th>
<th>Role 4</th>
<th>Role 5</th>
<th>Role 6</th>
<th>Role 7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultraperipheral nodes</td>
<td>Peripheral nodes</td>
<td>Non-hub connector</td>
<td>Kinless non-hub</td>
<td>Provincial hubs</td>
<td>Connector hubs</td>
<td>Kinless hubs</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>142</td>
<td>3,049</td>
<td>1,997</td>
<td>166</td>
<td>5</td>
<td>72</td>
<td>85</td>
<td>5,516</td>
</tr>
<tr>
<td>No IP</td>
<td>178</td>
<td>2,016</td>
<td>1,356</td>
<td>192</td>
<td>0</td>
<td>26</td>
<td>84</td>
<td>3,852</td>
</tr>
<tr>
<td>No STReP</td>
<td>36</td>
<td>1,906</td>
<td>1,175</td>
<td>73</td>
<td>1</td>
<td>33</td>
<td>45</td>
<td>3,269</td>
</tr>
<tr>
<td>No NoE</td>
<td>133</td>
<td>2,947</td>
<td>1,805</td>
<td>295</td>
<td>4</td>
<td>53</td>
<td>83</td>
<td>5,320</td>
</tr>
</tbody>
</table>

### Table 8: Topology of the ICT-RTD Network Against Removal of Participating Organizations (nodes) by Degree of Connectivity

<table>
<thead>
<tr>
<th>Topological property</th>
<th>Inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roles 1-7</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>5,516</td>
</tr>
<tr>
<td>Number of edges</td>
<td>119,663</td>
</tr>
<tr>
<td>Average degree</td>
<td>43.3876</td>
</tr>
<tr>
<td>Network density</td>
<td>0.0079</td>
</tr>
<tr>
<td>Network betweenness</td>
<td>0.1464</td>
</tr>
<tr>
<td>Assortativity coefficient</td>
<td>-0.1330</td>
</tr>
<tr>
<td>Number of components</td>
<td>1</td>
</tr>
<tr>
<td>Size of the largest component</td>
<td>5,516</td>
</tr>
<tr>
<td>Network diameter*</td>
<td>4</td>
</tr>
<tr>
<td>Characteristic path length*</td>
<td>2.5556</td>
</tr>
<tr>
<td>Clustering coefficient*</td>
<td>0.8334</td>
</tr>
</tbody>
</table>

*Computed on the largest component.
Figure 1: Partition of Nodes (Network Participants)

Source: Adapted from Guimerà and Amaral (2005a)