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Network structure and robustness: lessons for research programme design

Nicholas S. Vonortas[a]* and Koichiro Okamura[b]

[a]*Department of Economics and Center for International Science and Technology Policy, The George Washington University, 1957 E Street, N.W., Suite 403, Washington, DC 20052, USA;*
[b]*School of Business Administration, Kwansei Gakuin University, 1-155 Uegahara Ichiban-cho, Nishinomiya, Hyogo 662-8501, Japan*

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The information and communication technology (ICT) network of the last two European Research Framework Programmes (FPs) is deeply influenced by two distinct groups of organizations: a small group of hubs (3% of the participants) hold the key to keeping the network together and a second group of non-hub connectors large enough (39% of the participants) with a significant share of the overall networking activity 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 new FP (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

JEL Classification: L63; O3; O52

1. Introduction

Collaboration has become a pillar of the European approach to publicly supported research and technological development (RTD). Various forms of research collaborations have defined, more or less, all funding instruments/schemes of the Framework Programme (FP) for 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 FP for RTD – in order to meet Europe's ambitious objectives requires additional insights.

Naturally, the organizations and individuals that participate in FPs 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

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*Corresponding author. Email: vonortas@gwu.edu

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 article presents an empirical analysis of the emergent networks created and maintained by sustained public funding in information and communication technologies (ICTs) through the European Research FP. We analyse

- the positioning of European organizations in the ICT-RTD network,
- the identification of core organizations (hubs) and their effectiveness in creating and diffusing knowledge, and
- network robustness with regard 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 than 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) that maintain significant number of linkages outside their own module. The ICT-RTD network appeared to indicate a three-tier structure in the FP 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 FPs is deeply influenced by two distinct groups of organizations: a group of hubs amounting just to 3% of all network participants hold the key to keeping the network together as we know it and a second group of non-hubs large enough (39% of all participating organizations) and with a 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 – hitherto unidentified explicitly – has defied careful policy attention (the silent middle). It deserves 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 this 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 (IPs) look like the network backbone in terms of the sheer number and the network positioning of organizations and participations that they account for, Specific Targeted Research Projects (STRePs) are very important in terms of bringing new participants (more peripheral) into the network. Among the three examined instruments, Networks of Excellence (NoEs) are the least prominent in terms of structural effects on the network from their removal. Q1

The structure of the article is as follows. Section 2 describes the data and overviews network topology. Section 3 analyses network hubs and examines network effectiveness in producing and diffusing knowledge. Section 4 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 hand. Finally, Section 5 summarizes the main findings and discusses policy implications.

2. Data

In this article, the ICT-RTD network reflects the linkage between organizations through their participation in the projects funded by the Directorate Generale Information Society and Media (DG INFSO) during the sixth FP (FP6) (2002–2006) and the first 2 years of the Q2 seventh FP (FP7) (2007–2008). The analysed population consisted of 1923 collaborative RTD projects and 5516 unique organizations. Project and participant information was collected from the CORDIS database. The resulting network consisted of all dyadic linkages between these organizations as reflected in the analysed projects.

We used European Patent Office data to construct a separate Patent Citation 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 Citation Network was to select organizations akin to the ICT-RTD technological 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 International Patent Classification (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-KITeS database, we thus extracted all patents and patent citations corresponding to these IPC codes in the period 1990–2010.

The resulting dataset included all organizations (1642, 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 was 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.[2] The column FP6 + FP7 corresponds to the ICT-RTD network analysed in this study. The examined network is large: it comprises 5516 organizations that participated in 1923 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 such as this as is a small value of network betweenness suggesting that linkages

Table 1. Topological properties of the ICT-RTD network.

	FP (period)		
Topological property	FP6 + FP7 (2002–2008)	FP6 (2002–2006)	FP7 (2007–2008)
Number of projects	1923	984	939
Number of participants	21,367	12,578	8789
Average number of participants per project	11.1113	12.7825	9.3600
Number of nodes	5516	3977	2828
Number of edges	119,663	90,515	39,725
Average degree	43.3876	45.5192	28.0941
Network density	0.0079	0.0114	0.0099
Network betweenness	0.1464	0.152	0.1467
Assortativity coefficient	−0.1330	−0.1149	−0.0920
Network diameter	4	5	5
Characteristic path length	2.5556	2.5156	2.637
Clustering coefficient	0.8334	0.8462	0.8128

Notes: In all the three periods, all nodes are directly or indirectly connected with each other, respectively. That is, each ICT-RTD network consists of one component. Node, unique organizations in a network; edge, connection between nodes; average degree, average number of other nodes that 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 that network connection is concentrated in a certain group of organizations; assortativity coefficient, index measuring the tendency of organizations to connect to other organizations with similar degree. Positive values suggest that organizations connect to their kin (max value 1); network diameter, largest number of connections separating two organizations; characteristic path length: median of the average number of connections separating two organizations; clustering coefficient, index indicating the extent to which the organizations connected to a given organization also tend to be connected to each other.

among organizations are not concentrated around a particular group of organizations. The small value of the assortativity coefficient implies that local ‘neighbourhoods’ of organizations are formed in the network with a higher density among the included organizations and a lesser density with the surrounding area. Despite the large size of the network, participants may reach each other 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]

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 a network connector, that is, one connecting nodes that would otherwise remain unconnected. The existence and importance of such hubs in real-world networks have 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 maintain a disproportionately large number of links (scale-free network).[4] Such an uneven distribution of connections has prompted an extensive analysis to determine what turns organizations into network hubs and how network embeddedness affects the ability to benefit from networks and enhance performance (Granovetter 1985; Gulati 1998). Many empirical studies have reported higher performance for hub organizations (Echols and Tsai 2005; Uzzi and Gillespie 2002), suggesting an interest of hub organizations in network ‘orchestrating’ (Dhanarag and Parkhe 2006). One important consequence of the presence of such network hubs is that the overall connectivity of the network as well as its topological properties crucially depends on few important organizations. Such scale-free networks are robust to random removal of nodes but vulnerable to the targeted removal of the most important nodes, thereby decreasing the ability of the remaining nodes to interact with each other (Albert, Jeong, and Barabási 2000; Breschi and Cusmano 2004).

Hubs therefore have an extremely important role in partnership networks in terms of contributing to 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 neighbourhoods), based on a similarity metric. An example of such a well-known 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, 386–91). 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 the community membership of the nodes by classifying network nodes in a number of ‘system-independent’ universal roles based on their connectivity. The first step is to identify network modules[5] 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

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

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 the 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 a strong structure.[6] The ICT-RTD network has a modularity value greater than 0.3, suggesting a strong modular structure, and is made up of 18 modules, of which 5 largest modules keep 81% of the nodes in the network.[7]

After module partitioning, network nodes are classified according to the role that 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.

Within-module degree measures how well connected a node is to other nodes within its module. It is defined by

$$z_i = \frac{k_i - \bar{k}_{s_i}}{\sigma_{k_{s_i}}},$$

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 $\sigma_{k_{s_i}}$ 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

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

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.[8] 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 ($z < 2.5$)

- *Ultraperipheral nodes* (Role 1): Node has all its links within its module ($P = 0$).
- *Peripheral nodes* (Role 2): Node has a small positive participation coefficient ($P < 0.625$); that is, it has a large fraction of all its links within its module.
- *Non-hub connectors* (Role 3): Node has a fairly large participation coefficient ($0.625 < P < 0.8$); that is, 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 ($P > 0.8$); that is, it has very few links to nodes in its own module; it cannot be clearly assigned to any single module.

Hub nodes ($z \geq 2.5$)

- *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 with 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 presented in Table 2. Indicatively, organizations categorized as ultraperipheral 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

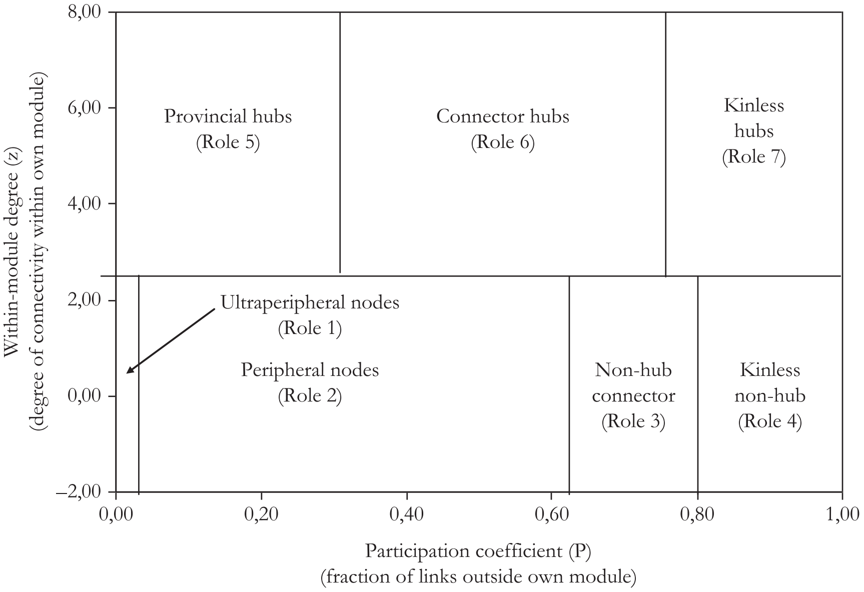

Figure 1. Partition of nodes (network participants).
Source: Adapted from Guimerà and Amaral (2005a).

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.[9] Finally, organizations categorized as non-hub connectors (Role 3) or non-hub kinless nodes (Role 4) have more linkages to other modules than those within their own modules. They are likely to be engaged in multiple projects (but not as actively as those in Roles 6 and 7).

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 these modules. Lastly, significant numbers of nodes in Roles 3–4 and Roles 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 three-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 presents the distribution of nodes by organizational type (industry, university, public research institute, and others) in the ICT-RTD network. Note that the university share in hub nodes is disproportionally large: a whopping 52% of all hubs are universities.

Table 2. Participating organization (node) distribution by role (ICT-RTD network).[10]

	Non-hub nodes				Hub nodes			
	Role 1	Role 2	Role 3	Role 4	Role 5	Role 6	Role 7	
Hub roles	Ultraperipheral nodes	Peripheral nodes	Non-hub connectors	Kinless non-hubs	Provincial hubs	Connector hubs	Kinless hubs	Total
Number of nodes	142	3049	1997	166	5	72	85	5516

Table 3. Network participant (node) distribution by organizational type (ICT-RTD network).

	Number of organizations (share, %)	
Organizational type	In the ICT-RTD network	Among hub nodes
University	876 (15.88)	85 (52.47)
Industry	3351 (60.76)	48 (29.63)
Public research institute	724 (13.13)	7 (4.32)
Others[a]	565 (10.24)	22 (13.58)
Total (%)	5516 (100)	162 (100)

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

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 regard to the FP 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 assessed 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 exploited the available patent data to derive various indicators of knowledge creation and diffusion. We used 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, that is, 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 used the following two indicators:

Table 4. Effectiveness in producing and diffusing knowledge (ICT-RTD network).

Effectiveness indicator (average over organization)[a]	Role 4	Role 5	Role 6	Role 7	Overall average for nodes in Roles 4–7
	Kinless non-hubs	Provincial hubs	Connector hubs	Kinless hubs	
Degree centrality	7.08 (29.62)	1.80 (2.49)	29.00 (59.14)	59.71 (107.87)	25.45 (68.40)
Betweenness centrality (×0.001)	0.35 (2.01)	0.24 (0.53)	1.78 (5.62)	5.61 (14.58)	2.03 (8.27)
Number of citations/patents received	0.225 (0.65)	0.600 (1.34)	0.418 (0.53)	0.543 (0.57)	0.36 (0.63)
Number of patents	153.65 (900.73)	3.20 (5.07)	860.29 (4032.82)	2954.41 (10,936.57)	1032.28 (6003.39)
Number of highly cited patents	2.28 (12.96)	0 (0)	21.46 (110.97)	58.78 (238.95)	21.09 (134.09)

[a] Standard deviation is given in the parentheses.

- *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,[11] 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 given in Table 4.

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 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 the 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. Nor 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 FPs appear to be a significant group and different from the other two categories that experts have focused on until now, that is, the core hubs and the peripheral organizations.[12]

4. ICT-RTD network robustness

4.1. Network robustness vis-à-vis funding instruments

We assessed the importance of the different funding instruments (IPs, STRePs, and NoEs) in determining the topological properties of the ICT-RTD network. To accomplish this, we conducted a *sensitivity analysis* that consisted of removing from the focal network all projects (and related organizations) funded according to specific measures and instruments and observed 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

Table 5. Distribution of FP projects by funding instrument after regrouping.

Framework Programme	Funding instrument				
	IP	STReP	CP	NoE	Total
FP6	253	669	n/a	62	984
FP7	221	687	908	31	939
Total	474	1356	908	93	1923

Table 6. Topological properties of the ICT-RTD network (sensitivity analysis).

Topological property	All	No IP	No STReP	No NoE
Number of projects	1923	1449	567	1830
Number of participants	21,367	13,047	10,806	18,881
Average number of participants per project	11.1113	9.0041	19.0582	10.3175
Number of nodes	5516	3852	3269	5320
Number of edges	119,663	63,503	92,566	94,230
Average degree	43.3876	32.9714	56.6326	35.4248
Network density	0.0079	0.0086	0.0173	0.0067
Network betweenness	0.1464	0.1516	0.1356	0.1601
Assortativity coefficient	−0.1330	−0.0948	−0.1278	−0.1198
Network diameter	4	5	4	4
Characteristic path length	2.5556	2.6836	2.3339	2.6023
Clustering coefficient	0.8334	0.8349	0.8343	0.8249

Notes: In all networks, all nodes are directly or indirectly connected with each other, respectively. That is, each network consists of one component.

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, the 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.[13] Table 5 presents the distribution of FP projects after regrouping.

Table 6 presents the results of the sensitivity analysis for the ICT-RTD network.[14] The column ‘All’ reports the values of the cumulative network of all project participants – that is, including all funding instruments – similar to the corresponding column in Table 1. The remaining columns report the results of the sensitivity analysis. For instance, the column ‘No IP’ reports the topological properties of the ICT-RTD network without IPs and it is similarly so 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 programme 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 30% of the organizations in the network only participate in IP-funded projects indicates that this instrument captures many organizations that otherwise would not participate in the FP.

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 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 an evaluation not 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 that otherwise would not have participated in the FP.

Overall, the observation of the network characteristics suggests that organizations participate in multiple projects across different programmes 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 are the least prominent in terms of structural effects on the network as a result of their removal. Q1

We also performed an additional sensitivity analysis to examine how the removal of different instruments influences the network in terms of the distribution of roles. The results are summarized in Table 7. In the first column, ‘All’ corresponds to the original ICT-RTD Q5 network – that is, including all funding instruments – the same as that in Table 1. The remaining rows report the results of the sensitivity analysis. For instance, the row ‘No IP’ reports the topological properties of the ICT-RTD network without IPs and it is similarly so for ‘No STReP’ and ‘No NoE’. Q6

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). The 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). The removal of STRePs results in very significant decreases across all categories, both hub and non-hub organizations.

Consistent with the prior sensitivity analyses described in this section, NoEs appear to be the least influential funding instrument across all networks. The story is different for IPs and STRePs. The removal of either IPs or STRePs results in 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 with the influence of STRePs that 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 a sensitivity analysis of the network by gradually removing groups of participating organizations in the different node categories shown in Figure 1.

Table 7. Participating organization (node) distribution by role in the network (sensitivity analysis).

	Non-hub nodes				Hub nodes			
	Role 1	Role 2	Role 3	Role 4	Role 5	Role 6	Role 7	
Network	Ultraperipheral nodes	Peripheral nodes	Non-hub connectors	Kinless non-hubs	Provincial hubs	Connector hubs	Kinless hubs	Total
All	142	3049	1997	166	5	72	85	5516
No IP	178	2016	1356	192	0	26	84	3852
No STReP	36	1906	1175	73	1	33	45	3269
No NoE	133	2947	1805	295	4	53	83	5320

Table 8. Topology of the ICT-RTD network against the removal of participating organizations (nodes) by degree of connectivity.

	Inclusive						
Topological property	Roles 1–7	Roles 1–6	Roles 1–5	Roles 1–4	Roles 1–3	Roles 1–2	Role 1
Number of nodes[a]	5516	5430	5356	5351	5178	3104	133
Number of edges	119,663	73,999	58,153	57,820	49,256	15,802	377
Average degree	43.3876	27.2556	21.7151	21.6109	19.0251	10.1817	5.6692
Network density	0.0079	0.005	0.0041	0.0040	0.0037	0.0033	0.0429
Network betweenness	0.1464	0.0591	0.0508	0.0511	0.0324	0.00441	0.00831
Assortativity coefficient	−0.1330	0.0231	0.0768	0.0776	0.1193	0.6075	0.862
Number of components	1	7	17	17	30	223	25
Size of the largest component	5516	5410	5295	5290	5067	2115	19
Network diameter[b]	4	7	8	8	8	15	2
Characteristic path length[b]	2.5556	2.9676	3.1782	3.1812	3.3531	5.6121	1.0232
Clustering coefficient[b]	0.8334	0.8075	0.7955	0.7957	0.7945	0.5888	0.1393

[a] Isolated nodes are excluded from the analysis. For example, the number of nodes of the network in the third column (Roles 1–7) is 5430, which is one less than the number of nodes in the second column (Roles 1–7), 5516 minus the number of Role 7 nodes, 85 (cf. Table 2). This is because the removal of Role 7 nodes from the original network results in 5430 nodes that are more or less connected with other nodes and one isolated node, the latter of which is excluded from the analysis.

[b] Computed on the largest component.

The 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’ reports the topological properties of the ICT-RTD network without kinless hubs (Role 7). The next column ‘Roles 1–5’ reports the topological properties of the ICT-RTD network without connector hubs and kinless hubs (Roles 6–7) and so forth.

The first observation is the huge effect of a small number of organizations in a single category: 85 kinless hubs (Role 7) (out of a total of 5516 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 in 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, 72 connector hubs (Role 6), has the next most significant influence on the ICT-RTD network. Its 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) and it is similarly so with the removal of 166 kinless non-hubs (Role 4), save for a large jump in the number of components. Q7

The next major change in the ICT-RTD network comes with the removal of non-hub connectors (1997 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 the total network participants).

Strongly suspected before and emphatically shown herein, the ICT-RTD network of the last two FPs 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 to keeping the network together. Interestingly, however, it is a third group of non-hub organizations (Role 3) large enough (38% of all participating organizations) and with a significant share of activity (linkages) that provides a base for the network. Absent these three groups of organizations, the network collapses into more than 200 unconnected sub-networks; knowledge flow among them is disrupted. They deserve significant attention from 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, and kinless non-hubs) involved organizations loosely connected to others in their own module. The remaining three hub categories (kinless hubs, connector hubs, and provincial hubs) involved 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, and provincial hubs) exhibited very low connectivity across modules. The remaining four strong connector categories (non-hub connectors, kinless non-hubs, connector hubs, and kinless hubs) exhibited much higher connectivity across modules. Kinless hubs (Role 7) stood out since they exhibited the highest levels of connectivity both within their own module and across modules.

Not surprisingly, the ICT-RTD network of collaborative RTD projects formed through the FPs was characterized as scale free, 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 that link extensively outside their own module. In fact, the ICT-RTD network appeared to indicate a three-tier structure in the FP 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 characteristic. 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 (USA), the University of Bremen (Germany), Oracle Corporation (USA), 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, Lemments, and Duysters 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, Behrens, and Krackhardt 2000).

One can argue that what we are observing in this article is this interplay where network participants find it advantageous to create strong social capital within a module as well as try to connect across 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 such as 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) that has defied policy attention till now (the silent middle). We believe that the designers of Horizon 2020 may want to pay attention to the latter group.

All said, this article puts forward a number of findings. First, the ICT-RTD network of the past two FPs 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 to 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 a significant share of the overall networking activity 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 this, 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 that 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 on the network from their removal.

We conclude 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 the one hand, and kinless and connector non-hubs, on the other hand – 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. A better understanding of both these features will make both the design of the new European Research FP (Horizon 2020) and its evaluation more effective.

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Notes

1. 5 March 2009 workshop on the state-of-the-art network methodologies for evaluating RTD programmes, organized by DG INFSO and DG Research. See Eustace (2009).
2. Matlab was used for the network analysis along with the sub-routines provided by Gleich (2008) for the detection of components and those reported by Mikail and Sporns (2010) for the hub analysis in the study.
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 large than the value (0.008) of the corresponding random network.
4. Scale-free networks are common in real-world networks. Examples include industry networks in life science and ICT sectors (Powell et al. 2005; Riccaboni and Pammolli 2002), co-authorship networks (Barabási et al. 2002), and shareholding networks in stock markets (Garlaschelli et al. 2005).

5. We use the terminology ‘module’ instead of ‘community’ or ‘cluster’ hereafter, following Guimerà and Amaral’s (2005a) terminology.
6. 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 a strong modularity structure include the air transportation networks (Guimerà et al. 2005), the Internet (Pastor-Satorras, Vázquez, and Vespignani 2001), and metabolic networks (Guimerà and Amaral 2005b).
7. Indicatively, the top five modules in the ICT–RTD network have 1142, 980, 940, 728, and 666 nodes, respectively.
8. We followed Guimerà and Amaral (2005a) and selected the limit values for the participation coefficient.
9. The five organizations categorized as provincial hubs (Role 5) in Table 2 include two regional governments, two engineering consultancies, and one accounting firm.
10. We also calculated this distribution for the ICT–RTD networks of FP6 and FP7 separately and found a similar distribution with the aggregate network presented here.
11. We conducted a series of ANOVAs to test for differences among categories (Roles 1–7) for all effectiveness indicators to verify that these categories were significantly different from each other. For all indicators, F-values ranged between 21.09 and 85.8 with p-values < 0.0001.
12. Kinless non-hubs (Role 4) and non-hub connectors (Role 3) together make up almost 40% of the body of participants (Table 2).
13. 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).
14. We also divided the samples into 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 the network size (i.e. number of nodes and number of links).

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