Order without hierarchy - the innovation ecology of a standard developing organization

Anke Piepenbrink
Azerbaijan Diplomatic Academy
Business School
apiepenbrink@ada.edu.az

Abstract
A Standard-developing organizations (SDO) is a voluntary inter-organizational collaborations to develop a global compatibility standard for an open modular system. A SDO is characterized by equal membership and hence lacks a hierarchy that assigns resources and tasks. Member organizations work jointly on innovations of the technological system, resulting in a two-mode innovation network between organizations and innovations. I study the emerging order in this network despite the lack of hierarchy. In particular I examine the existence and form of the emerging order, the underlying mechanism leading to its formation and its stability. I apply recent methods from ecological mutual systems as plant-pollinator networks to the innovation network of cellular telecommunications from 2001 to 2010. The match of organizations? resources with those required to develop innovations as tie formation mechanism explains basic structural properties as degree distribution and nestedness of the network. While the innovation network?s nestedness is rather stable over time, individual organizations can change dramatically as the catch-up of Chinese firms illustrates.
A Standard-developing organizations (SDO) is a voluntary inter-organizational collaborations to develop a global compatibility standard for an open modular system. A SDO is characterized by equal membership and hence lacks a hierarchy that assigns resources and tasks. Member organizations work jointly on innovations of the technological system, resulting in a two-mode innovation network between organizations and innovations. I study the emerging order in this network despite the lack of hierarchy. In particular I examine the existence and form of the emerging order, the underlying mechanism leading to its formation and its stability. I apply recent methods from ecological mutual systems as plant-pollinator networks to the innovation network of cellular telecommunications from 2001 to 2010. The match of organizations’ resources with those required to develop innovations as tie formation mechanism explains basic structural properties as degree distribution and nestedness of the network. While the innovation network’s nestedness is rather stable over time, individual organizations can change dramatically as the catch-up of Chinese firms illustrates.
INTRODUCTION

The locus of innovation for open complex systems — systems with a large number of components, interacting among each other (Simon, 1962) — is not any longer a single firm or a small group of firms, but the whole community or ecology of complex innovation (Dougherty & Dunne, 2011). Standard developing organizations (SDOs), voluntary inter-organizational organizations with the goal to develop a joint technological compatibility standard, are an example of such an ecology of complex innovation. The contribution of organizations to innovations is the major mechanism to influence the standard (Leiponen, 2008) and results in the innovation network within the SDO. While it is established that SDOs are socioeconomic systems for technological evolution (Tushman & Rosenkopf, 1992), it is an open question, whether order emerges in this ecology of equal partners without a formal hierarchy. Further questions are, which form this order may take, how it emerges and whether it leads to a stable system. This paper answers these question of emerging order by applying approaches of mutualistic systems or networks to the ecology of complex innovation in a SDO.

Ecological mutualistic systems are interaction networks between two different types of species, where both sides gain an advantage. Examples are pollinator-plant networks, where pollinating insects, while indulging themselves on the plants’ nectar, are pollinating these. These mutualistic systems can be described as two-mode or bipartite networks (Borgatti & Everett, 1997; Faust, 1997; Jordano, 1987; Wasserman & Faust, 1994), where animals as pollination insects belong to one type of nodes and the nectar spending plants to the other type. A central research question is the existence of order in the structure of these networks and the underlying formation processes as well as consequences, in particular the stability of the networks. The analogy of ecological mutualistic system to social systems was already drawn in a report on the stability of financial systems (May, Levin & Sugihara, 2008) and the collaboration of designers and manufacturers in the New York garment industry (Saavedra,
Reed-Tsochas & Uzzi, 2009; Saavedra, Stouffer, Uzzi & Bascompte, 2011). I draw on the analogy of the innovation ecology in SDOs to ecological mutualistic systems and use the developed methods in ecology as a framework of analysis to study the emergence of order in the innovation network of a SDO.

I conceptualize the innovation network in the SDO as a two-mode network, where organizations are one type of nodes and the innovations are the other type. The interaction or tie in the organization-innovation dyad is the decision of the organization to contribute to the innovation. I argue that this interaction provides mutual benefit to both partners of the dyad as organizations gain advantages in form of long-term royalty payments by implementing their proprietary technology into the standard and increase their legitimacy (Rosenkopf, Metiu & George, 2001; Waguespack & Fleming, 2009), while innovations only get into existence via the contribution of organizations. An important departure of this study from the approach by Saavedra et al. (2009, 2011) is the organization-innovation interaction rather than an organization-organization interaction. This emphasizes that both, organizations and innovations, are crucial elements of the ecology of complex innovations.

This study makes three contributions. First, it pushes the concept of ecologies of complex innovations (Dougherty & Dunne, 2011) one step further by applying ecological methods to an innovation ecology. These allow to analyze the emerging order, the underlying process as well as the stability of the order. Second, it applies a newly developed extension of nestedness to individual nodes that allows to study the individual contribution of nodes to the order of the system and their dynamics. Third, the organization-innovation interaction emphasizes that both, organizations and innovations, or more general — actors and their activity — are crucial elements of the ecology of complex innovations and the emergence and maintenance of order. The emerging nestedness of the network can serve as a principle of order in a variety of social systems without an a priori order.
I use data from Third Generation Partnership Project (3GPP), a SDO for cellular telecommunications, from July 2001 to December 2011 with 217 organizations and 436 innovations through the observation period.

The paper proceeds the following. After a review of the literature of mutualistic systems, overview of data and methods, I analyze the structure of the innovation network by comparing the structure of the innovation network with those of appropriate random and simulated networks. I end with a discussion of the findings.

THEORY

In this section I provide an overview over mutualistic systems in ecology\(^1\), including a definition, major structural properties (degree distribution and nestedness), underlying processes and stability of the system and how these approaches help to address the questions of emerging structure in the innovation ecology of an SDO. For each subsection I provide a summary of the current research of mutualistic systems and the implication for the SDO’s innovation network.

Definition, basic parameters and research approach

Mutualistic systems are complex systems that are defined by mutually beneficial interactions of species that belong to different types of species as animals and plants (Vazquez et al., 2009). Examples of mutualistic systems are plant-pollinator systems, where insects are pollinating plants while they are accessing their nectar, and seed dispersal systems, where birds eat the fruits of plants and disperse their seeds. Jordano (1987) introduced in his analysis of patterns of mutualistic systems their conceptualization as two-

mode networks. Building on the advances of complex networks the research of mutualistic systems as two-mode networks has seen an exponential growth in the last decade (Ings et al., 2009).

As shown in figure 1 key elements of this research is the understanding of the network structure, its underlying processes and consequences, in particular the stability of the systems under species extinction. Supported is the research by appropriate null models for networks and the definition of structural measures. The basic parameters that describe mutualistic systems are the number of nodes of both types (the species richness) and the density (called connectance). Mutualistic networks are rather small networks with a couple of dozens to a few hundred nodes for each type. There are typically more animals than plants in the system. The density is the number of ties in the network divided by the number of possible ties, the product of the number of animals and number of plants. It is with values between 0.02 and 0.3 low to moderately low (Olesen & Jordano, 2002) and decreases with the size of the network as ties typically scale with the species number, while the potential ties scale with the square of the species number. In the innovation network the two types of nodes are organizations and innovations with a mutualistic interaction and the framework of figure 1 is applied to this bipartite network.

The research approach of the literature of mutualistic networks seldom articulates explicit hypothesis, but compares empirical data with those of null models or random networks that contain implicitly the hypothesis. For the research questions of this study this translates into the following procedure:

**Question 1: Does order emerge in this ecology of equal partners without a formal hierarchy?**

The question translates into the comparison of the structural attributes of the innovation
network with those of appropriate null model networks. The degree distribution is one of the most studied structural properties and a significant difference of the empirical networks to random networks is an indicator of some order in the network.

**Question 2:** Which form may this order take? The question regarding the type of order is addressed by comparing nestedness of the empirical networks with that of random networks. In case an empirical network with a significantly higher degree of nestedness than a random network is considered to have a nested order\(^2\).

**Question 3:** How does this order emerge? This question addresses the underlying process. Several alternative processes of tie formation can be derived from theory and these are translated into network simulations. Again, the comparison of the empirical network attributes with those of simulated networks provide an answer whether a process fits the empirical data and whether it has a stronger predictive power than random networks.

**Question 4:** Does the order lead to a stable system? This question is broken down in two questions: The robustness of the network under removal of nodes. The removal of nodes can take various forms, the robustness of the network is measured and compared with a scenario of random removal. The second perspective is the stability over time and dynamics in the network attributes and relates to a comparison of networks over time.

Question 1 and 2 refer to the structure in figure 1, question 3 to the process and question 4 to the consequences. Random networks and their appropriate choice play a crucial role as they are the basis for the rejection of the null hypothesis that the empirical network is not different to the chosen type of random network. Equally important are the definition and measurement of network attributes.

\(^2\) Modularity as other candidate of structural property was tested and the empirical networks are less modular than random networks.
Structural properties

The major structural properties entail the degree distribution for each type of node and nestedness (Bascompte & Jordano, 2007; Vazquez et al., 2009).

**Degree distribution.** The *degree* is the number of nodes a focal node is connected to via a tie. In two-mode networks these connected nodes belong to the other type of node and a degree distributions for each types of nodes exists. With the seminal study of Barabasi & Albert (1999) and subsequent work it was shown that many complex networks in different fields are scale-free, where the degree distribution follows a power law without a characteristic scale of the system. The degree distributions for mutualistic systems are right-skewed as in other complex networks, however they do not show a pure power law distribution in most cases, but a truncated power-law (Jordano, Bascompte & Olesen, 2003; Medan et al., 2007)

\[ p(k) \propto k^\gamma \cdot e^{-k/k_c} \quad (1) \]

where \( p(k) \) is the probability to have the degree \( k \). The first term on the right-hand side in equation 1 is the power law term, where the exponent \( \gamma \) is the slope of the power law, a straight line in a double logarithmic chart. The second term is the truncation term that leads to a steeper decline after the cutoff point \( k_c \). While the truncation is also found in rather small social networks (Kogut, Urso & Walker, 2007), where the network size is a limiting factor to a *rich-get-richer* or *Matthew effect*, the key distinction to social networks is the exponent \( \gamma \) of the power law distribution. Jordano et al. (2003) found much smaller coefficients with a value of about one (on average 1.23 for animals and 0.84 for plants for pollination networks and 1.12 and 0.82 respectively for seed-dispersion networks) compared to values between 2 and 3 for social networks. The lower coefficient results in a less steep decline of the degree distribution of mutualistic systems compared to social systems.
**Nestedness.** Nestedness is the outstanding characteristics of mutualistic systems (Bascompte, Jordano, Melián & Olesen, 2003). While nestedness within one type or category means that a nested unit is completely contained in the next larger unit and both are contained in the next larger unit as in the example of Russian dolls or hierarchical organizations, nestedness in mutualistic systems is across the two types of species. In a completely nested system specialists, nodes with few links, interact with proper subsets of interaction partners of generalists (highly connected nodes). For the innovation network under study nestedness implies that organizations that contribute only to few innovations will choose innovations that are also supported by those organizations that work on many innovations. A consequence of a nested network is a core of highly connected nodes and a disassortative structure, where generalists are connected to specialists and hence leading to a cohesive system.

--- insert figure 2 about here ---

Figure 2 demonstrates nestedness (or its absence) for three different networks. All three networks are sorted with rows and columns along their degrees, i.e. for rows the high degree nodes (generalists) are at the top and the low degree nodes (specialists) at the bottom, for the column nodes high degree elements are at the left and low degree nodes at the right. In networks ordered in such a manner nested networks are characterized by the concentration of ties in the upper left part of the network. In the completely nested network in figure 2a the upper left part is completely connected, while the right bottom part of the network lacks ties. In contrast the random network (figure 2b) does not reveal any specific pattern. The observed example of a pollinator network (figure 2c) exhibits the tendency of connections in the upper left side, but has also deviations from the idealistic purely nested structure.

---

3 Ulrich, Almeida-Neto & Gotelli (2009) reviewed the literature of nestedness in ecology research.
Nestedness is an order resulting in the cohesion of the network with an integration of the densely connected group of generalists with specialists. It can be an alternative model to the network orchestration by a single lead firm (Langlois & Robertson, 1992) that substitutes the typical hub and spoke structure with the strong dependence on the technology sponsor in a one-mode perspective to the ordered system of a heterogeneous ecology of organizations and innovations in a two-mode perspective. This network in the one-mode projection will resemble the decentralized network as described by Langlois & Robertson (1992). The group of generalists together with the integrative, cohesive character can lead to a rather high stability of the network (see below), which is beneficial to the value creation and innovativeness of the system (Dhanaraj & Parkhe, 2006; Madhavan, Koka & Prescott, 1998).

Null models

The pure values of structural properties alone do not yet reveal, whether they are noteworthy or just random. They require the comparison with an appropriate null model or random network — a technique that became popular with the work on small worlds by Watts & Strogatz (1998). The choice of an appropriate null model is not an easy task (Gotelli & Entsminger, 2001; Gotelli & Ulrich, 2012; Ulrich et al., 2009). For two-mode networks several null models are used with different constraints. The least constraint networks are random networks that preserve the density and roughly the node number and are based on an equal probability of tie formation for each cell in the incidence matrix⁴ (fixed density or FD). An additional constraint is the preservation of the degree distribution of either rows (fixed row or FR) or columns (fixed column or FC). The most severe constraint is to keep the degree distribution of both types simultaneously (fixed row fixed column or FRFC). In addition Bascompte et al. (2003) used a null model where the probability of a tie is the average of its rows and column ties or occupancies (probable row column or prc). This is one of the most

---

⁴ The incidence matrix is a network representation in matrix form, where one type of nodes defines the
often used null model in the literature as it has a reasonable level of constraints. Recently Bluethgen, Fruend, Vazquez & Menzel (2008) suggested null models where the degree distribution for the null model is drawn from an underlying distribution as the lognormal distribution rather than the empirical degree distribution (lognormal null model).

**Process**

As the structure of networks can have profound impact on their stability and vulnerability (Albert & Barabasi, 2002; Bastolla et al., 2009; Burgos et al., 2007), the question of the processes leading to these properties becomes crucial in order to steer the system to a sustainable structure. For mutualistic systems two theories prevail for tie formation: The *neutrality* and the *forbidden links* hypothesis. The basic assumption of the neutrality theory is that the probability of interaction between animals and plants is uniformly distributed and hence the greater abundance of a species leads to more interactions. While the abundance of species can explain part of the structural properties, they are not sufficient to reconstruct the observed patterns (Krishna, Guimaraes Jr, Jordano & Bascompte, 2008; Vazquez, Chacoff & Cagnolo, 2009). In contrast the forbidden link theory assumes that some interactions are impossible or forbidden by the matching of phenomenological traits or trait complementarity of the species. For instance insects may not be able to reach into the corolla of a flower to get to the nectar or small birds are not able to carry rather larger fruits (Stang, Klinkhamer & van der Meijden, 2006). A fruitful way forward in disentangling the processes leading to a nested structure are simulations, where random networks are created with a tie formation probability either based on the neutrality or forbidden link assumption or a mix of both (Krishna et al., 2008; Rezende, Lavabre, Guimaraes Jr, Jordano & Bascompte, 2007; Santamaria & Rodrıguez-Girones, 2007). The simulations can be seen as a specific type of random networks, where the theoretical assumptions provide additional constraints to the preservation of the network’s density. In the simulation studies typically between one
hundred and one thousand networks are simulated and the average of their structural properties are compared to those of empirical networks.

A well-established patterns in the tie formation in inter-organizational networks is importance of social capital in form of past as well as existing ties between two potential partners. However, the tie formation in two-mode networks between organizations and activities is a novel perspective. The neutrality theory maps to the amount of SDO resources of an organization, while the forbidden links hypothesis refers to the match of an organizations resources and those required to develop the innovation.

**Dynamics**

The dynamics of the system is the change of the structure of the network over time and the changes on node level. Only few studies analyzed the temporal evolution of mutualistic networks over years due to the difficulty of data collection. Of the few studies that exist most cover only a short period of two to four years (Alarcon, Waser & Ollerton, 2008; Olesen, Bascompte, Elberling & Jordano, 2008). The most comprehensive study by Olesen, Stefanescu & Traveset (2011) stretches over twelve years, which confirmed the rather stable structure over time on the network level. The species number of plants as well as the network density were constant, while the number of animal species increased slightly in the long-term trend, though there were fluctuations on a yearly base. In contrast to the stable network level, there was a considerable amount of changes on the species level.

For the SDO the temporal stability or evolution provides insight in the vitality of the network in form of ongoing innovation activities and attraction of new organizations to the system. Fluctuations within the period may be due to different phases of the technological evolution as e.g. transitions from one generation to the next. While the network as a whole may be found rather stable as in the ecological systems, the stability or its dynamics on the node level addresses the question of openness of the SDO innovation network. In case a new
generation of the standard induces new inflow of organizations, can these newcomers assume prominent roles as e.g. hub or connectors in the network?

**Ecological and social networks**

Though mutualistic systems are in most cases different to social systems (Burgos, Ceva, Hernandez, Perazzo, Devoto & Medan, 2008; Montoya et al., 2006), recent research has successfully applied ecological methods to social systems (May et al., 2008; Saavedra et al., 2009, 2011). Saavedra et al. (2009) used simulations to reproduce the degree distribution, nestedness and modularity of ecological and social mutualistic systems. Their empirical context for the social networks are collaborative contracts as ties between contractors (designers), one set of nodes, and manufacturers, the other set of nodes, in the New York garment industry. These networks show similar properties than the ecological mutualistic systems. Saavedra et al. (2009) were able to reconstruct seventy percent of the structural properties of both, ecological and social, networks by their simulations with only three basic input parameters (the size of each type of nodes, designers and manufacturers, and the number of ties between them). They used two processes for their simulation: specialization and interaction. The specialization rule determines with how many partners a manufacturer will interact and it is defined by a uniformly distributed reward trait that its service provides. This rule does only apply to manufacturers. The interaction rule is based on trait complementarity, where the traits of contractors are also uniformly contributed.

Similar to Saavedra et al. (2009, 2011) I apply the methods of mutualistic ecological systems to a social collaborative innovation network. A key difference to the networks of the garment industry is that the nodes are organizations and innovations, rather than two organizations. The network can be seen as mutualistic, as organizations benefit by contribution to innovations and innovations come only into existence by the contribution of organizations. The benefits of organizations depend on their role in the system: technology
providers as component and equipment providers gain long-term royalty payments in case their proprietary technology is endorsed into the standard (Rosenkopf et al., 2001) as well as legitimacy (Fleming & Waguespack, 2007). For technology users, the network operators, active contribution is the only way to get their specific needs implemented into the standard and hence support their strategy.

DATA AND METHODS

The Data

I use data from 3GPP, a SDO for cellular telecommunications (3GPP, 2011). The standard development work is conducted by member organizations of 3GPP, which are either firms in the cellular telecommunication ecosystem, research institutes, universities or national ministries. The majority of the members are firms in the industry and its value chain with component suppliers as semiconductor firms, test equipment or software firms, equipment and cellphone vendors and network operators (Leiponen, 2008). The members are from about thirty countries from three major regions: Western Europe, North America and East Asia. The standard evolves via a stream of heterogeneous innovations, where bundles of innovations define so-called releases of the standard. I use data from July 2001 to December 2010. During this period 241 organizations were active and 489 innovations were jointly developed in six different releases (Release-5 to Release-10). This period covers most of the third generation of the standard and its evolution into the fourth generation (Release-8 and onwards). The start of the observation period in July 2001 is due to incomplete coverage of innovation regarding the supporting organizations prior to it.

The network under study is the innovation network within 3GPP, a binary two-mode network between organizations and innovations. The network is constructed in the following way: 3GPP provides a so-called work-plan, a list of all its innovations. For each innovation
following information is provided: the start and end date, the involved technological meetings/modules, and the supporting organizations. Normally organizations decide at the start of an innovation to support it and continue this support until the innovation is completed. The support of an innovation requires according the working rules of 3GPP an active contribution of the organization to the innovation (3GPP, 2011). A tie between an organization and an innovation exists in case the firm is one of the supporting organizations and it persists from the start to the end date of the innovation. As the work plan only provides the information of support or not support, the ties are binary and take the values of one in case a firm supports, i.e. contributes, to an innovation and zero otherwise. The innovation networks are constructed on a monthly basis.

In addition to the innovation network the technological profiles of the innovations and organizations are constructed. Based on the roster of 3GPP, which lists for each meeting the working group, the participating individuals and their affiliated organizations and the date, for each organization its technological profile is created on a quarterly base: It is defined by the number of individual participants affiliated with this organization for each working group. It is defined on a quarterly base as meetings take place typically every quarter. In case of high work load meetings are every six weeks — in these cases the average over the two meetings is calculated. Similarly the profile of the innovations is constructed based on involved working groups in its development. In contrast to the profiles of organizations this profile is binary as only the presence or absence of a working group is available. The profile for innovations is constant over its lifetime.

In the analogy of ecological networks I conceptualize organizations as pollinators and innovations as plants. The profiles define the match between organizations and innovations similar to matching traits in ecological systems. The argument is that organizations can only contribute to an innovation if they possess some of the capabilities that are required to develop it. The sum over the organizational profile for a given quarter defines the total
number of the organization’s SDO resources at this time — it is the analogy to abundance of animals of ecological systems. The innovations all share the same abundance of one.

**Methods**

The basic properties of the network and structural analysis uses well established network measures for two-mode networks (Borgatti & Everett, 1997; Vazquez et al., 2009). A short summary of the measures is provided in table 1.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of organizations $N_o$</td>
<td>Number of rows in the incidence matrix</td>
</tr>
<tr>
<td>Number of innovations $N_i$</td>
<td>Number of columns of the incidence matrix</td>
</tr>
<tr>
<td>Number of ties or links $L$</td>
<td>Number of filled elements in the incidence matrix</td>
</tr>
<tr>
<td>Density of the network</td>
<td>Number of ties / Number of possible ties $(\frac{L}{N_o \cdot N_i})$</td>
</tr>
<tr>
<td>Degree</td>
<td>Number of directly connected nodes to focal node (row or column margin of the incidence matrix)</td>
</tr>
</tbody>
</table>

Table 1: Measures used in the structural analysis of the innovation network.

**Nestedness.** Nestedness can be measured in several ways. I use the so-called $NODF$ (Almeida-Neto, Guimarães, Guimarães, Loyola & Ulrich, 2008), which has been widely adopted since its introduction. It measures the percentage of overlap of ties for pairs of rows and columns (nested overlap). The network wide nestedness is the average over all pairs, where the degree of one row (columns) is less than the degree of the other. The $NODF$ measure lies between 0 and 100, where 0 marks no nestedness and 100 complete nestedness. The $NODF$ measure also provides nestedness measures for the columns and rows separately. I extend the nestedness measure to the individual node level based on the concept of two-mode clustering (Latapy, Magnien & Vecchio, 2008).
Simulations. The procedure of simulations is similar to the steps for a simulation model of trait complementarity (Rezende et al., 2007), with the technological modules or working groups are identified as traits.

Step 1. I define the technological profiles of organizations and innovations as described above. The organization’s profile is drawn at the time where the innovation starts, as this is the time when the decision on support and hence contribution to an innovation is made. Step 2. The match of traits is the technological overlap between organization $i$ and innovation $j$ for a given cell $ij$ of the incidence matrix. For the first two models I use the Manhattan metric with the sum of overlap between the two profiles in each working group, standardized by the number of working groups the innovation is assigned to (Cantner & Graf, 2006). The first model, binary match, calculates the technological overlap of both profiles, where the profile of the organization is dichotomized, i.e. for each technological module it can take either zero (no resources) or one. The rationale is that organizations can contribute, independent of the size of their resources. The second model, valued match, keeps the information how many resources an organization has for each technological module. The third model, Jaffe, uses the Jaffe overlap or mean-centered correlation between the two technological profiles, the most often used metric for technological overlap (Jaffe, 1986). The fourth model, SDO resources, solely measures the total number of resources of an organization — it applies equally to all innovations.

Step 3. The simulation of tie formation based on the probabilities as defined by the second step. The probability is proportional to the matching between the two profiles. In order to preserve the density of the empirical networks these propabilities are normalized such, that their sum is identical to the density of the empirical network. In case of the abundance or resource hypothesis the first and second step can be skipped and the probability in step three will be defined by the SDO resources of the organization, rather than the match (Krishna et al., 2008).
Step 4. For each of the simulations the structural analysis is performed and compared with the empirical values and those of appropriate random networks.

RESULTS

First I analyze the structure based on the two degree distribution and the nestedness and then the stability of the networks, including robustness and dynamics. For each step I compare the empirical result with those of random and simulated networks.

I use the statistical package R, version 14.1, to perform the analysis. The package igraph (Csardi & Nepusz, 2006) is used for neighborhoods in the individual nestedness measure, the package bipartite (Dormann et al., 2008) is used for the degree distribution analysis and the lognormal random networks, the package vegan (Oksanen et al., 2011) is used to calculate random networks as well as the nestedness. I developed additional code for the individual nestedness measure and for the prc random network and the network simulations.

Degree distribution

As the degree distribution depends on the network size, I use the standardized degree to make the results comparable over all months, following the approach by Saavedra et al. (2009). The standardized degree is the degree divided by the average degree of the node type \(L/N_i\), where \(L\) is the number of ties and \(N_i\) is the number of nodes of the types under consideration).
narrow distribution, which indicates a stable distribution of the standardized degree over the observation period of nearly ten years. This is in particular remarkable as the average degree for organizations has doubled in the first half of the observation period and it shows that the degree distribution scales with the average degree. The distribution is best described by a truncated power law (blue line) with a slope of 0.57 and a cutoff at about six of the standardized degree, i.e. the average degree. The distribution is rather flat, reflecting the low average exponent of the truncated power law. The average coefficient of the (non-standardized) degree distribution over all months is 0.64 with a standard deviation of 0.14. This exponent is much closer to those of ecological mutualistic systems (1.23 and 1.12 for animals in pollinator and seed dispersal networks and 0.84 and 0.82 for plants) and far below the values between two and three typically reported for social networks (Albert & Barabasi, 2002) and the theoretical value of three for a preferential attachment process (Barabasi & Albert, 1999).

In the following I compare the degree distributions of the empirical network with those of the degree distributions of simulated networks. For each simulation 100 networks were simulated and the degree distributions show the average degree over the simulated networks. Figure 3b compares the fitted truncated power law (blue line) of the empirical networks with fits of a truncated power law to simulated networks based on four different processes (red lines). Neither the fitted curves to simulations, based on a binary match (dashed line) or Jaffe overlap (dashed-dotted line) can reproduce the empirical distribution. Both the simulations based on valued match (dotted line) and the amount of resources (long dashed line) provide qualitatively good fits with the truncated power law (blue line). Both are remarkably similar and only differ marginally in the range beyond the cutoff point. While they overestimate the distribution for smaller values of the standardized degree, they are closer to the empirical values for large standardized degrees.
Figure 3c and 3d show the analog figures for the degree distribution of innovations. This distribution is even more narrow and hence more stable than that of organizations. In contrast to organizations, this distribution is best described by an exponential distribution with a steep decline for standardized degrees beyond 0.5, which indicates that innovations have a rather well defined degree around the average standardized degree, however degrees up to four times of the average standardized degree occur. All simulated networks show a very similar distribution, which generally reproduce the empirical distribution rather well, however they are slightly shifted to the right, hence showing more innovations with larger degrees compared to the empirical distribution.

As the simulations based on binary match and Jaffe overlap fail to reproduce the degree distribution, I focus in the following on the simulations based on valued match and amount of resources together with the random network of probability-row-column (prc) and random networks based on an underlying lognormal distribution.

--------------- insert figure 4 about here ---------------

For sake of completeness I compare in figure 4 the empirical degree distribution with those of two types of random networks (prc and lognormal). For organizations (left side) both random networks provide a poor description of the empirical degree distribution and fall short compared to the simulations of valued match and resources. For the degree distribution of innovations, however, both are rather close to those of the empirical network, similar to the simulations. I conclude that the two-mode network has a structure different from appropriate null models.

**Nestedness**
Figure 5 shows the nestedness of the monthly innovation networks and the comparison with two random and two simulated networks. First, the nestedness of the empirical network fluctuates around the level of 25, with the highest values of about 30 at the beginning of the observation period and the lowest value of about 21 in the year 2003. The amount of the fluctuation becomes smaller and the cycles shorter with increasing time.

The nestedness of the prc random networks (figure 5a) is with a level of 15 significantly smaller than that of the empirical network. It shows similar fluctuations than the empirical network, however less pronounced. The nestedness of lognormal random networks (figure 5b) is still smaller than the empirical network, however it is on a level of about 20 and it reproduces well the fluctuations of the empirical network. Both random networks have rather small error bars.

While both random networks are less nested for the whole observation period, the two simulation networks show a different behavior. The valued match simulation (figure 5c) is at the beginning and end of the observation period more nested than the empirical network, while it is less nested from 2004 to 2007, largely during the development of Release-7. The simulation based on the amount of resources reproduces well the empirical nestedness in the beginning and end, when the valued match is too high, and is far too small in the years from 2004 to 2007. These results suggest, that there was a shift in the underlying formation process, with the dominance of the resource based process at the beginning and the end and the valued match process in the period in between.

---

5 For each random and simulated network type I performed a t-test for each month comparing the empirical nestedness value with those of the random/simulated networks resulting in significantly different values
Dynamics

The nestedness were already presented for the full period in the previous sections and is relatively stable despite the increase of the number of innovations until 2009 and the number of organizations since 2009, hence changing network size. The stability of the innovation network over nearly ten years, though with fluctuations, raises the question of stability on the individual node level. I use the individual nestedness to study the stability of nodes contribution to the nestedness of the network. The individual nestedness is in particular suitable, as nestedness is the key property of network order, which also influences the robustness of the network.

While innovations change from release to release organizations can and do persist over the observation period and are the focus of figure 6. It depicts the percentage that the individual nestedness contributes to the network’s nestedness of the six organizations with highest nestedness in July 2001 (Ericsson, Nokia, Siemens, Motorola, Vodafone and Nortel) and in December 2010 (Huawei, Ericsson, Alcatel-Lucent, China Mobile, NSN, ZTE ). Ericsson (figure 6a) is the only organization that is in the top six in the first and last observation month and kept its top position. Nokia (figure 6b) has steadily lost individual nestedness, however if its 50 percent joint venture with Siemens, Nokia-Siemens Networks (NSN), is taken into account, it still has a major contribution to the nestedness of the network, while Siemens does not any longer contribute in 3GPP with the formation of the joint venture. Motorola (figure 6c) started from a already considerably lower level and decreased its nestedness to about half of its level in July 2001. Vodafone (figure 6d), one of the world’s largest network operator is loosing nestedness since Release-7, when work on the fourth generation started. Nortel (figure 6e) is an example of a firm that indeed got out of business after a steady
decrease in its individual nestedness. Alcatel-Lucent (figure 6f), a merger between Alcatel and Lucent, entered the top six by combining two high, but not top, nested organizations.

The next three examples are from China, two equipment manufacturers (Huawei and ZTE) and one network operator (China Mobile), with marginal to low nestedness in July 1001 after they joined 3GPP end of the 1990s and were in December 2010 within the top six after an enormous catch-up. Huawei (figure 6g) had in December 2010 the largest individual nestedness after a very steep increase in the year 2008. China Mobile (figure 6h), the now world’s largest network operator, as well as ZTE show strong increases of individual nestedness from 2007 onward, the period were the development of the fourth generation started.

This example of these former and/or current top nested organizations demonstrates high dynamics below the rather stable "surface" of the network properties. These are the most extreme examples, where the catch-up of the three Chinese organizations alone leads to the rearrangement of more than 40 percent of the nestedness within four years.

DISCUSSION

I have developed a model of the innovation ecology in a SDO, a community of organizations without formal hierarchy that jointly develop and evolve a technological standard via a stream of innovations. While this parsimonious model is a simplification of the real world, it offers insights into the complexity of the innovation ecology, which I put in a broader perspective. First, the conceptualization of the innovation ecology as a mutualistic system explains the emergence of order, second I discuss in how far the framework can be transferred to other contexts. Lastly, I discuss limitations and directions of future research.

The innovation ecology as mutualistic system
I conceptualize the innovation ecology in a SDO as a mutualistic system and develop a model of the emergence of order in this system by applying methods of ecology. The development of this model consists of two steps: In step one, I extend the ecology beyond the participating organizations by including the innovations, in which the organizations are jointly involved and contribute to, as equally important elements. This allows the conceptualizing of the innovation ecology as two-mode network with organizations and innovations as network nodes and mutualistic ties or interactions between them. In step two, I apply methods of ecological mutualistic network analysis to study the structure of the innovation network.

First, the emerging order takes the form of nestedness, where specialists, organizations supporting only a few innovations, mainly contribute to innovations supported by generalists and analogous for innovations. Nestedness leads to a dense core where generalists are connected among each other and also to a disassortive behavior, where low and high degree nodes are connected, an uncommon characteristic in social networks. The large heterogeneity in the degree distribution of organizations reflects their role in the value chain, where high degree organizations are mainly equipment vendors or network operators. Component providers have a technical more limited scope and hence less opportunities to participate in innovations. Though innovations have a more narrow degree distribution, they show a considerable variation around the mean of about eight, double of the required number of supporters.

Second, the emergence of the structural properties can be well explained by a parsimonious process, the valued match of resources. The valued match process is actually a hybrid between match and resource or abundance as it measures the amount of available resources in each technical area required for the development of the innovation and is actually a n-fold combination of abundance processes, where n is the number of areas of expertise required for the innovation.
Third, the innovation network has a remarkable stable structure over the nearly ten years of its analysis with a stable density, standardized degree distribution and nestedness despite its growth. Though the nestedness shows fluctuations and some cyclic behavior, it is rather stable on network level over the ten years. However, on the level of individual nodes the picture changes completely with a high variability over time. The catch-up of Chinese firms demonstrates the openness of the ecology.

In summary, the innovation ecology in the SDO possesses a nested structure based on a resource-based process, where the stability of the ecology on network level is accompanied by dramatic changes on the individual node level. The emerging order is not that of a hierarchy of nearly decomposable subsystems, but elements or nodes of the system are nested across different types of nodes. The nestedness of the system is an example of emergence, where the interaction of two types of nodes leads to the novel property of the system.

**Applicability of the model to other contexts**

The successful transfer of the model of mutualistic ecological systems to the innovation ecology in 3GPP raises the question whether a next, less distant, transfer to other social actor-activity systems appears fruitful. In order to answer this question it is worth to summarize the implicit and explicit assumptions of the model.

First, there is a set of actors, a set of potential activities or problems to be solved and capabilities required for the activities possessed by the actors. Though this appears trivial, in case of an emerging industry it may not be clear, who are the actors, what are the problems that need to be solved and what are the required capabilities. The distinction between actor and activity also implies that the decision is made by the actor, while the activity is subject to the decision. Second, the tie between the actor and activity is mutualistic and provides benefits for both. Third, a process of fit between actor and activity drives the decision
process. This implies transparency on the activities for a given competence field at a given point of time and full eligibility for all actors to participate. This in particular assumes that there are no additional ties between actors or activities that influence the decision of the actors, i.e. the decisions of the actors are independent. Fourth, the process of matched resources assumes an appropriability regime that provides benefits based on the contributions to the activities. It also assumes that these contributions are measurable and transparent. Fifth, it assumes broad-scale capability profiles with a spectrum of actors ranging from many specialists to few generalists.

Though this is a stringent list of assumptions, which will seldom, if at all, be met in reality, it is more about whether these assumptions are met to a large degree. In the example of a SDO the formation of the SDO facilitates the first assumption and its mission of standard development the second and broad-scale profiles satisfy the fifth assumption. While a SDO also provides transparency and eligibility, the condition of no further influencing ties among actors is not fully met, however I argue that these ties are less important than those of interest. Similarly for the fourth assumption, while there is an IPR regime that supports appropriability, there are other mechanisms as market success, where the SDO participation is only one of many elements.

An example to which the model may apply are consulting firms. They have a formal order, however are less hierarchical than large traditional firms. The boundary of the consulting firm defines the actors (consultants, project leaders and partners), activities in form of consulting projects, and competencies as industry expertise or practices. The tie provides benefits for both sides as actors need to be involved in projects and projects need actors. There may not be full transparency and choice, and yet staffing will be largely based on the fit between the task and capabilities. The assumption of broad-scale capabilities is imperfectly given with three types of roles with increasing generalist capabilities from consultants over project leaders to partners. On project side this assumption is given with
different types of projects with small size projects dominating. While the emerging structure of membership in customer projects is not the official structure in a consulting firm it may have important consequences for the knowledge flow and cohesion within the firm.

The establishment of a home for the innovation ecology can be seen as the very first task of public policy. A current example of converging industries is the ongoing development of smart grids, the future, more efficient electrical grid. In Europe the development of smart grids is embedded in the EC’s long-term roadmap and strategy. Five focus areas were identified: standard development, consumer data protection, a regulatory framework for incentives, an open retail market, and innovation support (EC, 2011). The activities of the European Union include the bridging of industries. ”The Commission will continue bringing together the energy and ICT communities within an expert group to assess the network and information security and resilience of Smart Grids as well as to support related international cooperation.” (EC, 2011, page 9).

**Limitations and directions for future research**

While this study looks promising in the endeavor of understanding ecologies of complex innovation, it is a very first step with a number of limitations.

One limitation is the dichotomy of the innovation network as it does not allow to distinguish between organizations that contribute only marginally and those that are the power horses in the development of an innovation. The same applies to innovations, which range from incremental extensions to existing functionality to radical innovations in the transition from the third to the fourth generation and required contributions will largely vary. Furthermore, innovations are assumed to be exogenous, while they come into existence via proposals by organizations and hence there is a dependence between the two types of nodes. I also ignore direct relationships between organizations and innovations, while in reality customer-supplier or competitive relationship exist, collaborative ties via alliances or
embeddedness in local environments. Also innovations are related, in particular over time, where a new service as location based service is enhanced over time creating a sequence of innovations over time. While the research context of SDO with rules to facilitate knowledge mobility and IPR appropriability is ideal to focus on structure and stability, it is also a limitation. First, the study covers only one SDO and may not be representative for other SDOs, second, more critical, the specific environment does not allow to transfer these results to other inter-organizational ecologies.

In addition, the nature of this study with the transfer of a research approach and agenda from one discipline to another is rather broad. The findings of this study point to directions of future research. Within 3GPP’s context the study of SDO resources as combinations of valued match, the refinement of measures matched profiles and the understanding, whether the lack of full agreement of simulations and empirical data is based on measurement or the process are potential future directions.

In a more general framework the understanding of the sensitivity of the resulting network structure on the technological profiles is important. How important is the specialist-generalist distribution of capabilities to achieve the resulting structure? Is there a key difference between one generalist and ten generalists — for actors and for activities? The answers to these questions may answer the question of key differences between sponsor-orchestrated networks and SDOs. They may also provide insights on the importance of the simultaneity of narrow and broad innovations in the emergence of order.

The assumption of independent choice of activities by actors is often not met in reality. The study of two simultaneous processes, capability match and additional attracting or repulsing forces will make the model applicable in a broader context.
References


Figure 1: Overview of the key topics and supporting methods in the analysis of mutualistic systems.

Figure 2: Examples of networks with differing degree of nestedness: a completely nested network (a), a random network (b) and an empirical mutualistic network (c). Adopted from Bascompte et al. (2003).
Figure 3: The cumulative distribution of the standardized degree for all months in the observations period and fit of exponential, power law and truncated power law for organizations (a) and innovations (c) and the comparison with fits to simulated networks based on four different processes for organizations (b) and innovations (d).
Figure 4: The cumulative distribution of the standardized degree for all months in the observations period for organizations (a) and innovations (b) and the comparison with fits to two random networks (prc and lognormal).
Figure 5: Nestedness of monthly two-mode innovation networks (red dots) and nestedness of random and simulated networks (grey dots including error bars of one standard deviation) ((a) prc, (b) lognormal, (c) valued match and (d) amount of resources.)
Figure 6: The evolution of individual nestedness for selected organizations.