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(Article begins on next page)

Enterprise Cluster Dynamics and Innovation Diffusion: A New Scientific Approach

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Abstract. A model in the field of enterprise management is described in this work. Its main goal is to represent and analyze the dynamics and interrelations among innovation diffusion and enterprise clusters formation and modifications. A formal description of the model is given, along that of its main parameters. Qualitative results are described. Clustering is definable as the tendency of vertically and/or horizontally integrated firms in related lines of business to concentrate geographically, or, to a more general extent, virtually. Innovation is a critical factor for the competitiveness of a National System, especially when the economy of the latter has come to maturity. However, the diffusion of innovations among its potential adopters is a complex phenomenon.

Keywords: Innovation diffusion, enterprise network, simulation, model.

1 Introduction

The studies about innovation prove that, beside the creation of innovations, it is also crucial to study their diffusion in the system in which the firms work and cooperate, i.e.: the network.

At that level, it is important to clarify what an enterprise network is and why the firms start to cooperate inside the network for diffusing an innovation.

A collaborative network is a whole of nodes and ties with a different configuration based on of what it has to achieve. These concepts are often displayed in a social network diagram, where nodes are the points and ties are the lines. The idea of drawing a picture (called a "sociogram") of who is connected to whom for a specific set of people is credited to [5], an early social psychologist who envisioned mapping the entire population of New York City. Cultural anthropologists independently invented the notion of social networks to provide a new way to think about social structure and the concepts of role and position [7], [8], [23], an approach that culminated in rigorous algebraic treatments of kinship systems [29]. At the same time, in mathematics, the nascent field of graph theory began to grow rapidly, providing the underpinnings for the analytical techniques of modern social network analysis.

The nodes represent the different organizations that interact inside the network and the links represent the type of collaboration between different organizations.

The organizations could be Suppliers, Distributors, Competitors, Customers, Consultants, Professional Associations, Science Partners, Incubators, University, and so

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on. The kind of partner firms linked over a network looks to be related to the type of innovation occurring: for example incremental innovators rely more frequently on their customers as innovation partners, whereas firms that have totally new products for a given market are more likely to collaborate with suppliers and consultants. Advanced innovators and the development of radical innovations tend to require a tighter interaction with universities. This point is supported by [15] in a survey of 4.564 firms in the Lake Constance region (on the border between Austria, Germany and Switzerland). By examining the interactions among firms, customers, suppliers and universities it emerges that firms that do not integrate their internal resources and competences with complementary external resources and knowledge show a lower capability of releasing innovations [14].

Philippen and Riccaboni [26], in their work on "radical innovation and network evolution" focus on the importance of local link formation and the process of distant link formation. Regarding the formation of new linkages Gulati [20] finds that this phenomenon is heavily embedded in an actor's existing network. This means that new ties are often formed with prior partners or with partners of prior partners, indicating network growth to be a local process. Particularly when considering inter-firm alliances, new link formation is considered "risky business" and actors prefer alliances that are embedded in a dense clique were norms are more likely to be enforceable and opportunistic behavior to be punished [18], [21], [28], [2]. Distant link formation implies that new linkages are created with partners whom are not known to the existing partners of an actor. At the enterprise level, [6] shows that distant linkage that serve as bridge between dense local clique of enterprises, can provide access to new source of information and favorable strategic negotiation position, which improves the firms' position in the network and industry.

In order to analyze the complex dynamics behind link formation and innovation diffusion, as long as their relationships, an agent based model is introduced in this work, and is formally analyzed.

2 Network Shape, Collaboration and Innovation Diffusion

The ties representing collaborations among firms can be different in structure, type and number.

- type of ties: strong or weak (depending on the type of collaboration: contracted development, licensing, research partnerships, joint venture, acquisition of an owner of a given technology);
- structure of ties: long or short (for example industrial districts in which firms are geographic clusters or virtual clusters); reciprocal or not (firms that exchange competences each other or simply give/take);
- number of ties: dense or not (depending on the number of links among the firms).

The type and the number of ties affect the network efficiency: for example, a network composed of relationships with partners comprising few ties among them would enable control for the principle partner. A network of many non-overlapping ties would provide information benefits: in [30] the authors suggest that the number of collaborative relationships a firm is involved in, is positively related to innovation output while, conversely, closed networks have been found to foster innovation more than open ones [9]. A network composed of partners with many interlocking and redundant ties would facilitate the development of trust and cooperation.

The firm's position inside the network is as important as the number and type of ties. In [6] the authors find that rather than maximizing the number of ties, firms should strive to position themselves strategically in gaps between different nodes, so to become intermediaries. Contrary to this perspective, [3] propose that the best position is one where all the firms are tied only to the focal actor. On the other side, [4] suggests that the benefits of increasing trust, developing and improving collaboration and reducing opportunism shapes network structures creating cohesive interconnected partnerships. These consequent studies highlight that there is no consensus about which the optimal networking configuration should be. The configuration depends on the actions that the structure seeks to facilitate.

The firms start to collaborate inside a network for different reasons:

– risk sharing [16]
– obtaining access to new markets and technologies [17];
– speeding products to market [1];
– pooling complementary skills [12];
– safeguarding property rights when complete or contingent contracts are not possible [22];
– acting as a key vehicle for obtaining access to external knowledge [28], [10].

The literature on network formation and networking activity therefore clearly demonstrates that whilst firms collaborate in networks for many different reasons the most common reason to do so is to gain access to new or complementary competencies and technologies. Those firms which do not cooperate and which do not formally or informally exchange knowledge and capabilities limit their knowledge base on a long-term and ultimately reduce their ability to access exchange relationships.

When the innovation start to circulate, it can affect the network collaboration efficiency: firms can decide to cooperate inside the network by developing an external exploration behavior, meaning that a firm decides to be related to other organizations in order to exchange competences and innovations. Otherwise if the firm considers its internal capability to create innovation as a point of strength, or if the cost of external exploration is perceived as higher than that of internal research, then it could prefer to assume an internally explorative behavior in which it tries to create new competences (and possibly innovations) inside the organization itself.

During the process of innovation diffusion the network can change in the number of actors (exit and entry), and in numbers and patterns of link information [2]. The network can expand, churn, strengthen or shrink. Each network change is brought about by specific combination of changes in tie creation, tie deletion, and by changes in an actor's portfolio size (number of link) and portfolio range (numbers of partners) [2]. It's normal that the modification depends on the original structure of the network.

Also the propensity to collaborate inside a network affects innovation diffusion. When a network is a highly collaborative one, the innovation tends to diffuse more quickly, if the ties are dense, non redundant, strong and reciprocal. If the network is a collaborative one, but the ties are weak or unidirectional, the innovation spreads slowly and could not reach all the nodes in the network.

To explore and analyze these complex social dynamics, an agent based model is described in the following paragraphs, that keeps into account most network and enterprise variables.

3 Agent Based Simulation

Why do enterprises team up? There can be many reasons for this strategy, leading, in its widest extent, to the creation of joint-ventures, i.e.: a new economical subject formed by two or more enterprises with the goal of new projects, or of clusters and networks of enterprises. The leading cause for these phenomena is the optimization of the production, by resources and competences sharing. Agent based simulation is an effective paradigm for studying complex systems. It allows the creation of virtual societies, in which each agent can interact with others basing on certain rules. The agents are basic entities, endowed with the capacity of performing certain actions, and with certain variables defining their state. In the model presented here, the agents are reactive, meaning that they simply react to the stimuli coming from the environment and from other agents, without elaborating their own strategies. When the model is formally built and implemented, it can be run by changing a parameter at a time, and emergence of a complex behavior occurs.

Agent based Modeling is thus one of most interesting and advanced approaches for simulating a complex system: in a social context, the single parts and the whole are often very hard to describe in detail. Besides, there are agent-based formalisms which allow studying the emergence of social behavior through the creation and study of models, known as artificial societies. Thanks to the ever increasing computational power, it has been possible to use such models to create software, based on intelligent agents, whose aggregate behavior is complex and difficult to predict, and which can be used in open and distributed systems.

In [11] we read that: “An autonomous agent is a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future”.

Another very general, yet comprehensive definition is provided by [24]: “…the term [agent] is usually applied to describe self-contained programs which can control their own actions based on their perceptions of their operating environment”.

Agents have traditionally been categorized as one of the following types [16]: Reactive; Cognitive/Deliberative; Hybrid.

When designing any agent-based system, it is important to determine how sophisticated the agents' reasoning will be. Reactive agents simply retrieve pre-set behaviors similar to reflexes, without maintaining any internal state. On the other hand, deliberative agents behave more like they are thinking, by searching through a space of behaviors, maintaining internal state, and predicting the effect of actions. Although the line between reactive and deliberative agents can be somewhat blurry, an agent with no internal state is certainly reactive, and one that bases its actions on the predicted actions of other agents is deliberative.

The agents used in this paper are reactive, but organized in the form of a MAS (Multi Agent System), which can be thought of as a group of interacting agents working together or communicating among each other. To maximize the efficiency of the system, each agent must be able to reason about other agents' actions in addition to its own. A dynamic and unpredictable environment creates a need for an agent to employ flexible strategies. The more flexible the strategies however, the more difficult it becomes to predict what the other agents are going to do. For this reason, coordination mechanisms have been developed to help the agents interact when performing complex actions requiring teamwork. These mechanisms must ensure that the plans of individual agents do not conflict, while guiding the agents in pursuit of the system goals. Many simulation paradigms exist; agent-based simulation is probably the one that best captures the human factor behind decisions. This is because the model is not organized with explicit equations, but is made up of many different entities with their own behavior. The macro results emerge naturally through the interaction of these micro behaviors and are often more than the algebraic sum of them. This is why this paradigm is optimal for the purposes of modeling complex systems and of capturing the human factor. The model presented in this paper strictly follows the agent based paradigm and employs reactive agents, as detailed in the following paragraph.

4 The Model

The model is built in Java, thus following the Object Oriented philosophy and has been engineered and built at the e-business L@B, University of Turin. This is suitable for agent based modeling, since the individual agents can be seen as objects coming from a prototypal class, interacting among them basing on the internal rules (methods). While the reactive nature of the agents may seem a limitation, it's indeed a way to keep track of the aggregate behavior of a large number of entities acting in the same system at the same time. All the numerical parameters can be decided at the beginning of each simulation (e.g.: number of enterprises, and so on). Everything in the model is seen as an agent; thus we have three kinds of agents: Environment, Enterprises and Emissaries (E^3). This is done since each of them, even the environment, is endowed with some actions to perform.

4.1 Heat Metaphor and the Agents

In order to represent the advantage of an enterprise in owning different competences, the "heat" metaphor is introduced. In agent based models for Economics, the metaphor based approach [19] is an established way of representing real phenomena through computational and physical metaphors. In this case, a quantum of heat is assigned for each competence at each simulation turn. If the competence is internal (i.e.: developed by the enterprise) this value is higher. If the competence is external (i.e.: borrowed from another enterprise) this value is lower. This is realistic, since in the model we don't have any form of variable cost for competencies, and thus an internal competence is rewarded more. Heat is thus a metaphor not only for the profit that an enterprise can derive from owning many competences, but also for the managing and synergic part (e.g.: economy of scale).

Heat is also expendable in the process of creating new internal competences (exploitation) and of looking for partner with whom to share them in exchange of external competences (exploration). At each time-step, a part of the heat is scattered (this can be regarded as a set of costs for the enterprise). If the individual heat gets under a threshold, the enterprise ceases its activity and disappears from the environment. At an aggregate level, average environmental heat is a good and synthetic measure to monitor the state of the system.

The *Environment* is a meta-agent, representing the environment in which the proper agents act. It's considered an agent itself, since it can perform some actions on the others and on the heat. If features the following properties: a grid (X,Y), i.e.: a lattice in the form of a matrix, containing cells; a dispersion value, i.e.: a real number used to calculate the dissipated heat at each step; the heat threshold under which an enterprise ceases; a value defining the infrastructure level and quality; a threshold over which new enterprises are introduced; a function polling the average heat (of the whole grid). The environment affects the heat dispersion over the grid and, based on the parameter described above, allows new enterprises to join the world.

The *Enterprise* is the most important and central type of agent in the model. Its behavior is based on the reactive paradigm, i.e.: stimulus-reaction. The goal for these agents is that of surviving in the environment (i.e.: never go under the minimum allowed heat threshold). They are endowed with a heat level (energy) that will be consumed when performing actions. They feature a unique ID, a coordinate system (to track their position on the lattice), and a real number identifying the heat they own. The most important feature of the enterprise agent is a matrix identifying which competences (processes) it can dispose of. In the first row, each position of the vector identifies a specific competence, and is equal to 1, if disposed of, or to 0 if lacking. A second row is used to identify internal competences or outsourced ones (in that case, the ID of the lender is memorized). A third row is used to store a value to identify the owned competences developed after a phase of internal exploration, to distinguish them from those possessed from the beginning. Besides, an enterprise can be "settled", or "not settled", meaning that it joined the world, but is still looking for the best position on the territory through its emissary. The enterprise features a wired original behavior: internally or externally explorative. This is the default behavior, the one with which an enterprise is born, but it can be changed under certain circumstances. This means that an enterprise can be naturally oriented to internal explorative strategy (preferring to develop new processes internally), but can act the opposite way, if it considers it can be more convenient. Of course, the externally explorative enterprises have a different bias from internally explorative ones, when deciding what strategy to actually take.

Finally, the enterprise keeps track of its collaborators (i.e.: the list of enterprise with whom it is exchanging competencies and making synergies) and has a parameters defining the minimum number of competencies it expects to find, in order to form a joint. The main goal for each enterprise is that of acquiring competences, both through internal (e.g.: research and development) and external exploration (e.g.: forming new links with other enterprises). The enterprises are rewarded with heat based on the number of competences they possess (different, parameterized weights for internal or external ones), that is spread in the surrounding territory, thus slowly evaporating, and is used for internal and external exploration tasks.

The *Emissaries* are agents that strictly belong to the enterprises, and are to be seen as probes able to move on the territory and detect information about it. They are used in two different situation: 1) if the enterprise is not settled yet (just appeared on the territory) it's sent out to find the best place where to settle. 2) if the enterprise is settled and chooses to explore externally, an emissary is sent out to find the best possible partners. In both cases, the emissary, that has a field of vision limited to the surrounding 8 cells, probes the territory for heat and moves following the hottest cells. When it finds an enterprise in a cell, it probes its competencies and compares them to those possessed by its chief enterprise verifying if these are a good complement (according to the parameter described in the previous section). In the first case, the enterprise is settled in a cell which is near the best enterprise found during the movement. In the second case, the enterprise asks the best found for collaboration).

While moving, the emissary consumes a quantum of heat, that is directly dependant on the quality of infrastructures of the environment.

The movement of the emissaries is based on reactive rules; it follows the hotter cells it meets on its path and, if an enterprise is found, it checks for the complementary competences, in order to propose a link with the parent enterprise.

In the following paragraph a formal insight of the model is given through a set of defining equations, for the agents and the general rules.

5 Underlying Formal Equations

In order to formally describe the model, a set of equations is described in the following.

The multi agent system at time T is defined as:

$$\mathrm{MAS_T} = < \overline{\mathrm{E}}, \overline{\mathrm{e}}, \overline{\varepsilon}, \overline{\mathrm{link}} > . \tag{1}$$

Where $\overline{\mathrm{E}}$ represents the environment and is formed by a grid $\mathrm{n} * \mathrm{m}$, and a set $\overline{\mathrm{k}}$:

$$\begin{cases} \overline{\mathrm{E}} = < n * m, \overline{\mathrm{k}} > \\ \quad \mathrm{n}, \mathrm{m} > 0 \end{cases} . \tag{2}$$

Where the set $\overline{\mathrm{k}}$ definines the heat for each cell, $\overline{\mathrm{e}}$ is the set of enterprises with cohordinates on the grid, and $\overline{\varepsilon}$ is the set of the emissaries, also scattered on the grid:

$$\begin{cases} \overline{\mathrm{k}} = < \mathrm{k_{i,j}} > \\ \overline{\mathrm{e}} = < \mathrm{e_{i',j'}} > \\ \overline{\varepsilon} = < \varepsilon_{\mathrm{i}'',\mathrm{j}''} > \\ 0 < i, \mathrm{i}', \mathrm{i}'' \leq \mathrm{n} \\ 0 < j, \mathrm{j}', \mathrm{j}'' \leq \mathrm{m} \end{cases} . \tag{3}$$

Each enterprise is composed by a vector $\vec{\mathrm{c}}$, and an emissary (ε_e). The vector $\vec{\mathrm{c}}$ defines the owned competences, with a length L and competences $\mathrm{C_l}$ represented by a boolean variable (where 1 means that the $\mathrm{l^{th}}$ competence is owned, while 0 means that it's lacking):

$$\begin{cases} e_{i,j} \ni \vec{c}, \varepsilon_e \\ \vec{c} = (L, C_l) \\ 0 \le l \le L \\ C_l = \text{Boolean} \end{cases} \quad (4)$$

In $T = t > 0$, $k_{i,j}$ that's the heat of each cell on the grid, depends on the heat produced by the enterprises (K_e) and the dispersion effect (d). The heat of each enterprise is function of the competences it possesses and of the behavior it carried on in the last turns (b_e).

$$\begin{cases} k_{i,j} = f(K_e, d) \\ K_e = f(\vec{c}_e, b_e) \\ b \in \bar{b} \\ \bar{b} =< set\ of\ behaviors > \end{cases} \quad (5)$$

In particular, a certain behavior can be successful, meaning that at the end of a phase of internal or external exploration, a new competence (internal or outsourced, respectively) will be possessed. Otherwise, a it's unsuccessful when, after some steps of research and development (internal exploration) or external market research to find a partner, nothing new is found, and thus the l^{th} competence remains zero.

$$\begin{cases} \begin{cases} \text{if } (b = \text{success}) \text{then } C_l = 1 \\ \text{else } C_l = 0 \end{cases} \\ b \in \bar{b} \end{cases} \quad (6)$$

At each time-step the set of links (connecting two enterprises together) is updated basing on the competences of the enterprises.

$$\begin{cases} \overline{\text{link}} =< link(e_{i,j}, e_{i',j'}) > \\ \text{link}(e_{i,j}, e_{i',j'}) = f(\overrightarrow{c_{e_{i,j}}}, \overrightarrow{c_{e_{i',j'}}}) \end{cases} \quad (7)$$

Specifically, when an enterprise does external exploration, it looks for a good partner, i.e.: an enterprise with a number of competences to share. So, if an enterprise with a vector like [1|0|0|0|1] meets one with a vector like [0|1|1|1|0] then there is a perfect match and the two enterprises will create a link among them, to share the reciprocally missing competences. This is the perfect situation, but not the only one in which two enterprise can create a link; in fact, it's enough that there is at least one competence to reciprocally share. The strength of the link is directly proportional to the exchanged competences. This set of equations and rules is enough to explore the effects on the network of the behaviors of the enterprises, namely the way in which the firms are managed (externally or internally focused). Though the model allows also to explore the effects on innovation (i.e.: a competence that's possessed only by one enterprise).

In $T = t' > t$ a radical innovation can be metaphorically introduced in the system (this is called "shock mode", since this is decided by the user, at an arbitrary step) by means of increasing the length of the vector of competences of a specific enterprise:

$$\begin{cases} L \leftarrow L+1 \\ C_{l+1}(\boxed{e}) = 1 \\ C_{l+1}(\bar{e} - \boxed{e}) = 0 \end{cases} . \tag{8}$$

Meaning that the competence C_{l+1} will be possessed by only one enterprise, at that time, while the same competence will be lacking to all the others; though, all the enterprises' vectors will increase in length, meaning that potentially all of them will be able to internally develop that new competence through R&D, from then on.

The vector length metaphorically represents the complexity of the sector (industry) in which the enterprises operate; an highly technological sector has many more potential competences than a non-technological one. So, another kind of "shock effect" to the system is that of increasing the length of the vector by more than one component, and by leaving all the new components to zero for all the enterprises. In this way, they'll have to develop themselves the new competences by means of internal exploration. The analysis phase is carried on after several steps after t', in order to see how the introduction of the innovation impacted the network and the enterprise in which the innovation was first introduced. So we have an analysis phase in $T = t'' > t'$ defined as:

$$\begin{cases} MAS_{t'} \text{vs } MAS_{t''} \\ I \rightarrow d\theta \text{ link};\ d\theta\, e; d\theta\, k \end{cases} . \tag{9}$$

Namely, the comparison among the system at time $t'$and the same system at time t'', since the innovation has differential effects on the number (and nature) of the links, on the number of enterprises and the heat of the cells composing the environment, always depending on the managerial behavior of the involved enterprises. At the beginning of a simulation, the user can change the core parameters, in order to create a particular scenario to study and analyze.

6 Conclusion and Qualitative Results

The impact of innovation diffusion on the network depends on the collaboration degree of the system. If the network is collaborative the diffusion of innovation strengthens the ties and increases the number of the links among organizations. The firms are more inclined to exchange competences than to create them inside the organization: they favor an externally explorative behavior that obviously strengthens the network. In order to study the complex social dynamics and interrelations among innovation diffusion and collaborative/non-collaborative networks, an agent based model is introduced in this work and described in details. Even if beyond the purpose of the present work, some qualitative results coming from the simulator are given here, in order to show that this model can be effectively used as a tool for studying the dynamics of different base scenarios. As shown in figure 1 and figure 2, where some output graphs obtained from the E^3 simulation model are depicted, a collaborative network (A1) is defined by the existence of a large number of strong ties (compared to the number of enterprises). In our example, there are 10 strong ties among the enterprises. In a network structured in this way, the introduction and consequent diffusion of an innovation strengthens the collaborations through:

- An higher number of ties
- Ties that get even stronger (A2). In particular, the existing links get stronger and new ties are created ex novo.

In this case, the "shock effect" described in the previous paragraph introduces effects in the networks that affect the decree of collaboration of the network itself. The introduction of an innovation in the network strengthens the links among the enterprises and the collaboration efficiency increases.

On the other side, in the case of a network with low propensity to collaboration the strong links do not exist or are a few when compared to the number of enterprises. The introduction of innovation in a network structured in this way can affect the degree of collaboration of the enterprises, according to industry complexity. In this situation (B1), it's possible to notice two different scenarios. If industry complexity is not too high (e.g.: the textile industry), as represented in B2, the number of ties is low and the firms prefer to create innovation inside the organization than receiving it from other organizations: in this case the firms favor internal exploration. So, when the complexity is low, the propensity to collaboration does not change and the enterprises are still loosely connected. The number of links could even increase, but much more slowly compared to the case of a collaborative network (B2 vs A2).

If industry complexity is high (B3), the diffusion of innovation increases the number of ties (but less than in a collaborative network) but the structure of ties is weak: in this case, again, the firms prefer an externally explorative behavior. So, in this case, the propensity to collaborate gets higher than before after the introduction of an innovation, but the links are always weaker when compared to the case of a collaborative network (B3 vs A2).

The analysis carried on through an agent based model allow to study "in the lab" a social system, like an enterprise network, and to study the effects of an innovation on collaborative and non-collaborative networks. While the purpose of this work is the description of the model itself, the qualitative results show that the innovation diffusion in a network can create new ties among the enterprises (can thus be regarded as a driver for ties creation in a network). Though, only in a collaborative network, or in a non-collaborative network acting in a complex industry, the number of the links increases significantly, while in non-collaborative networks acting in an industry which is not too complex, the number of links among the enterprises stays more or less the same, even after the introduction of the innovation (the enterprises being more focused on internal explorative behavior).

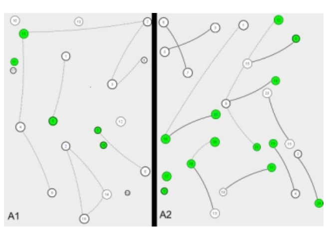

Fig. 1. Collaborative network before (A1) and after (A2) the introduction of an innovation

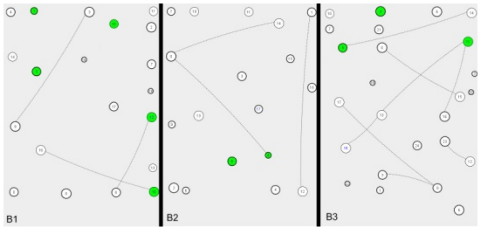

Fig. 2. Non-collaborative network before (B1) the introduction of an innovation. After (B2) in case of non complex industry, and after (B3) in case of complex industry.

The presented model is comprehensive and its scope is wide; it could be used to study the behavior of enterprises clusters and networks in many different scenarios and situations. In future works quantitative results will be given, and different situations will be analyzed.

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