On an Efficient Marie Curie Initial Training Network

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ABSTRACT

Collaboration in science is one of the key components of world-class research. The European Commission supports collaboration between institutions and funds young researchers appointed by these partner institutions. In these networks, the mobility of the researchers is enforced in order to enhance the collaboration. In this study, based on a real Marie Curie Initial Training Network, an algorithm to construct a collaboration network is investigated. The algorithm suggests that a strongly efficient expansion leads to a star-like network. The results might help the design of efficient collaboration networks for future Initial Training Network proposals.

KEYWORDS

Collaboration networks, strongly efficient networks, cooperative game theory

INTRODUCTION

Social network models are important for investigating collaboration and communication between people or organizations. Newman [1] has shown that the connectedness and closeness are useful definitions when analysing scientific collaboration. In addition, the average shortest path, the diameter (*i.e.* the maximum shortest path) and the density of such networks are useful measures for the comparison of networks or comparison of the partners within a network. However, cost and payoff (benefit) definitions are necessary for the investigation of the overall efficiency of the network. Jackson and Wolinsky [2], in the context of cooperative game theory, have introduced the connections

model and proven that a unique *star network*[1] maximizes the overall payoff of the network, in the case where the cost of maintaining a link is higher than the value of a link but low enough that overall payoff keeps increasing with new connections.

In this paper, an algorithm for designing an efficient Marie Curie Initial Training has been investigated. The collaborative network is assumed to consist of fourteen partner institutions and seventeen early stage researchers (ESRs). Each partner hires at least one ESR and each ESR must visit two other partners. The lengths of the visits vary depending on the career development plan of each ESR. The strength of collaboration between any two partners is determined by the length of these visits; a longer visit implies more collaboration. Therefore the distance between any two partners is defined as the inverse of the total length of visits of the ESR(s) travelling from one partner to another. The problem considered in this study differs from the connections model of Jackson and Wolinsky [2] in that: (a) there is a primary network consisting of four founding partners, (b) the distances between partners vary according to the length of the ESR visits, and (c) there are three different payoff values that can be received from a created link.

DEFINITIONS AND PROBLEM DESCRIPTION

We have fourteen partners $\{P_1,...,P_{14}\}$. Each edge, ij, between partners P_i and P_j represents an undirected link and the *distance* between any two partners is defined as the inverse of the total length of the ESR visits. For example, in the case when the ESR of P_1 visits P_4 for three months and the ESR of P_4 visits P_1 for fifteen months, the distance between P_1 and P_4 becomes 1/(15+3)=0.05556.

The network consists of eight experimental and six computational partners. The partners $P_1, P_2, P_3, P_7, P_8, P_9, P_{11}$ and P_{14} are conducting experimental research; and partners $P_4, P_5, P_6, P_{10}, P_{12}$ and P_{13} are conducting computational research. The cost of creating a link is assumed to be equal throughout the network. However, the payoff of a created link depends on whether the link is between two computational (c–c) or two experimental (e–e) partners or between an experimental and a computational partner (e–c). The payoff, δ, is assumed to be highest for e–c, and lowest for c–c, *i.e.* $\delta^{e-c} > \delta^{e-e} > \delta^{c-c}$.

The aim of this study is to define an appropriate efficiency concept, propose an algorithm to find an efficient network, and then examine the final structure of the network from the point of view of both the partners and ESRs.

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[1] A star network is a star-shaped network with a central player such that all other players are connected to this central player.

We start with the network of four founding partners, denoted by g_f. Each founding partner hires one ESR. The length of visits of ESRs within the g_f have been decided at the beginning of the project, as shown in Table 1. Thus the distances between founding partners are already known, as shown in Figure 1. The distances are calculated as the inverse of the total visits of ESRs between any two partners. As new partners are linked sequentially, the network, g, expands in a way that an efficient network is constructed.

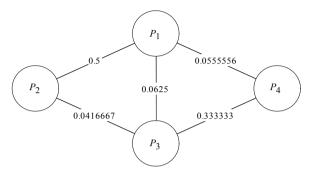|	P_1	P_2	P_3	P_4
$ESR_1 (P_1)$	0	0	8	3
$ESR_2 (P_2)$	2	0	16	0
$ESR_3 (P_3)$	8	8	0	0
$ESR_4 (P_4)$	15	0	3	0

Table 1. *Length (months) of visits of the early stage researchers (ESRs) within the founding network, g_f. ESR₁, ESR₂, ESR₃ and ESR₄ have been appointed by partners, P_1, P_2, P_3 and P_4, respectively.*

Figure 1. *Graph of the network of founding partners. The numbers along the edges represent the distances. The distance is defined as the inverse of the length of total visits of ESRs between any two partners.*

The net *individual payoff* that P_i receives from the network g is[2]

$$u_i = \sum_{\substack{j \neq i \\ j=1}}^{N} \frac{\delta_{ij}}{d_{ij}} - \sum_{j=1}^{M} c_{ij} \qquad (1)$$

where d_{ij} is the shortest distance between P_i and P_j, N is the number of partners, c_{ij} is the cost of creating a link and M is the number of direct links to P_i. The payoffs are specified as $\delta^{e-c} = 3$, $\delta^{e-e} = 2$ and $\delta^{c-c} = 1$. The cost of a link is assumed to be equal throughout the network, (*i.e.* $c_{ij} = 1$). According to the definition (1), each partner P_i benefits from indirect links while the cost only comes from the creation of direct links between P_i and its adjacent partners.

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[2] The definition in Eq. (1) is inspired from Jackson and Wolinsky [2]. However, in this study, it is based on the shortest distances in a different manner and there are three different payoff (δ) values.

The *value of the network g* is [2]

$$v(g) = \sum_{i=1}^{N} u_i \tag{2}$$

A network is referred to as *strongly efficient* [2] if its value is maximized on the set of all possible networks.

Definition: Let g_f be the network of founding partners. The *strongly efficient expansion* is the expansion of g_f by linking *m* new partners so that the value of the network is maximized on the set of all possible expansions.

The problem discussed here is to find a strongly efficient expansion of the founding network g_f according to the length of visits shown in Tables 1 and 2. There are three new partners (P_5, P_6 and P_7) that hire two ESRs while the other partners hire only one ESR.

P_5	ESR_5	9, 4
	ESR_6	8, 6
P_6	ESR_7	8, 4
	ESR_8	10, 4
P_7	ESR_9	9, 4
	ESR_{10}	6, 5
P_8	ESR_{11}	8, 7

P_9	ESR_{12}	10, 4
P_{10}	ESR_{13}	9, 5
P_{11}	ESR_{14}	10, 3
P_{12}	ESR_{15}	8, 5
P_{13}	ESR_{16}	8, 4
P_{14}	ESR_{17}	6, 3

Table 2. *Lengths (months) of visits of ESRs appointed by new partners. Each ESR must visit two other partners for the periods of time shown in the table. For example, ESR_5 is going to visit a partner for 9 months and visit another partner for 4 months.*

ALGORITHM

The algorithm for finding a strongly efficient expansion requires an exhaustive search on the set of all possible networks (without any prior knowledge leading to the solution). Even for ten new partners, this search is prohibitive. Carayol *et al.* [3], for a similar problem, suggested a genetic algorithm to construct an efficient communication network. However, in this paper, we use a simple heuristic algorithm.

Initially, all new partners are arranged in descending order according to the total mobility of their ESRs. In other words, the partner which sends its ESR(s) for longer periods of time to the other partners links first. The algorithm starts with g_f and links each new partner one by one to the most appropriate partners. It is assumed that the partners hiring two ESRs and sending them for longer times are more eager to collaborate and are more likely to host other ESRs. As they link first, other partners are able to link to these enthusiastic partners.

Algorithm:

1. *Calculate all shortest distances within the network of founding partners, g_f. Find the shortest distance matrix, M_{g_f} (which is a 4×4 matrix).*
2. *Divide each shortest distance by the appropriate payoff (δ) value and find the weighted shortest distance matrix, $W_{g_f}(i,j) = M_{g_f}(i,j)/\delta_{ij}$.*
3. *Do i=5:17*
   4. *Choose any two partners in the network:*

   Link the partner of ESR_i to these two partners. Calculate all shortest distances and divide each shortest distance by the appropriate payoff (δ). Find the average of all the elements of the weighted shortest distance matrix. Keep the expanded network with the minimum average weighted shortest distance.

   5. *If all pairs of partners are checked, go to 6 otherwise go to 4.*

6. *End Do.*

RESULTS AND DISCUSSION

Figure 2(a) shows that the algorithm leads to a star network around the founding partners. The partners in Figure 2(a) are coloured according to their individual payoff values, as defined in Eq. (1). The computational partner in the founding network, P_4, is the central partner. All new partners create a link to P_4, and eight new partners create a link to P_2. It is suggested that partners, P_2 and P_4, are the most convenient partners for hiring experienced researchers and for inviting scientists from outside the network. In addition, Figure 2(b) shows that the individual payoffs of the founding partners are higher than the other partners.
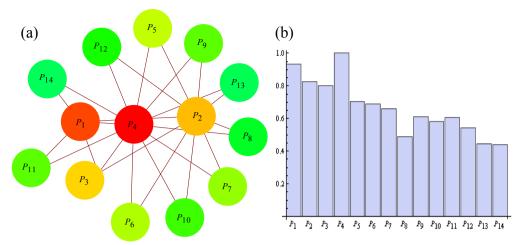
Figure 2. *(a) Graph of the final structure of the network. Partners are coloured according to their individual payoff values in Figure 2(b). (b) Normalised individual payoff values defined in Eq. (1).*

The results are examined using principal component analysis (PCA)[3]. The PCA reveals similar (or different) behaviour among the partners or among the ESRs. Since we have many partners and ESRs, the Euclidian (ordinary) distance has been used for clustering the partners or ESRs. Figure 3 shows that the founding partners and ESRs hired by the founding partners play significant roles in the final network. The method highlights the fact that although partners P_1 and P_3 have fewer connections compared to other founding members, their payoffs are relatively high. In addition, Figure 3(b) shows that ESR$_2$ and ESR$_4$ play crucial roles because they create the most important connections (associated with longer visits) within the founding network. It can be concluded that the length of visits of ESRs between founding partners are very important for the collaboration of the whole network.

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[3] PCA is a statistical technique for covariance analysis of multi-dimensional data. The method looks for the largest eigenvalues, and uses them for highlighting the most significant information (or the dominant pattern) hidden in the data. The eigenvectors corresponding to the largest eigenvalues are called the principal components. The first principal component is the eigenvector corresponding to the largest eigenvalue, and the second principal component is the eigenvector corresponding to the second largest eigenvalue.
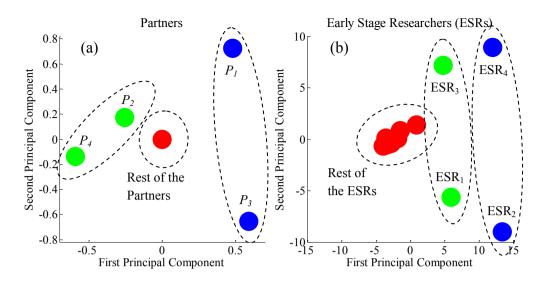
Figure 3. *PCA analysis of final structure of the network. The results are clustered using the Euclidian distance. Different colours are used to highlight the distinct clusters in the final network data. (a) Partners, (b) Early stage researchers (ESRs).*

ACKNOWLEDGEMENT

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