Physica A 471 (2017) 33–43

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Empirical research on evolutionary behavior of covert network with preference measurement

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HIGHLIGHTS

- An improved preferential measurement method for small size network is proposed.
- A real covert network data is used to analyze the three evolutionary behaviors.
- Multiple node properties are measured for preferential patterns analysis.
- Behavioral preference follows different distribution on specific node property.
- Numerical count and preference measurement could show different conclusions.

ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form 8 December 2016
Available online 15 December 2016

Keywords:
Preference measurement
Covert network
Evolutionary dynamics
Individual behavior

ABSTRACT

A key ingredient of studying the topological evolution of covert network is the individual behaviors which generate the evolutionary dynamics of covert organizational network. In this paper, we proposed an improved preference measurement method and used it to analyze three evolutionary behaviors of a real covert network, namely node addition, node deletion and link formation. Simulation experiment demonstrated that the improved method is robust on the small organizational network. The empirical study showed the specific pattern of evolutionary behaviors by offering direct quantitative support from preferential measurement. The measured property is then extended from degree to multiple node properties. The results indicate that the preferences of different behaviors follow different distributions with linear or nonlinear tendency across the process according to the type of node property. We conclude that the general scale-free network model is not suitable to model the evolutionary process of covert network.

1. Introduction

Understanding topological characteristic and evolutionary dynamics of the covert network (terrorist network, drug network, criminal group network, and so on) have attracted much attention in the last few years [1–9]. It is crucial for social security and construction of public policy. Most of the reported researches on studying the topological structure of the covert network employed *Social Network Analysis* (*SNA*) method and the results were gained based on a snapshot of evolving network. Some other works treated the covert network as temporal sequential networks (*Dynamic Network Analysis, DNA*)

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http://dx.doi.org/10.1016/j.physa.2016.12.006
0378-4371/

and the longitudinal changing tendency of structural characteristics was analyzed to investigate the evolutionary process with time [5,10,11]. These efforts have provided rich insights into the evolutionary process of the covert network. However, they studied the covert network from a social science perspective and the inherent evolutionary mechanism with formal quantitative measurement has not been taken into full consideration. Thus, they cannot well explain how the covert network forms, changes and how the structural characteristic is derived from the individual behavior.

Evolutionary dynamics are essential to gain fundamental understanding of real-world networks [12,13]. Because the process indicates the general organizing principle [14–16]. Even without the node addition, the network can evolve as individuals will interact with each other to add or delete link according to their requirement. Sageman's research of terrorist network showed that the terrorist network do not evolve at completely random [4]. The complex emergency derives from individual interaction and organized behaviors, which suggests that link formation does not occur randomly but depends on node properties. Individual interacts according to heterogeneous preference [17–19]. Regarding network growth, the most influential model is the BA model [20], which generates scale-free network by two simple mechanisms, growth and *preferential attachment*. These two behaviors produce the evolutionary dynamics and determine the topological characteristic of the network. After that, many authors measured the preferential attachment effect in real networks [15,21–26]. Variant methods for preferential measurement are proposed [27]. Some other works have studied different preferential attachment mechanisms for system complexity, such as hierarchical preferential attachment [28], spatial preferential attachment [29], local information preference [30]. Most of the reported models are built based on the node growth and assume that the nodes and edges will not disappear in the evolutionary process. However, the node may be lost in real world network. Some works studied the deletion problem and they found that when the network is large and the growth is much larger than the deletion, the result of network evolution is the same as the growth network [18,31]. Most of these studies focus on large complex networks, and few research studies traditional social networks, such as organizational network [6]. Existing quantitative estimation of preferential behavior on covert network and consequent validation of modeling assumptions are rare.

There are three problems while using the preferential measurement to study covert network. First, the network size is not always growing. The nodes can be removed, which makes the size decreases or maintains unchanged. Second, some analysis requires growth data of networks with precise time stamps of the vertex and link creations [32], which is impractical for data of covert network. Third, the most significant difference between complex network and organizational network is that the individual behavior in the latter network follows certain organizational principles instead of completely self-organized rule. Variant individual behaviors generate networks with different topological characteristics. The first two problems need the measuring method robust and the last one indicates that the preference may show diversity in measuring different covert network or different node property.

In this paper, after the problem description and formal definition of three evolutionary behaviors in covert network, we propose an improved preferential measurement method, which can be used to measure the behavioral preference of small organizational network and non-integer individual property. Furthermore considering attachment mechanism difference, a simulated experiment is designed to test the effectiveness of the proposed method on four growing networks with different preferential attachment mechanisms. Followed that, an empirical investigation on a real covert network data is performed by utilizing the proposed method and the measured node property is extended from single degree to multiple node properties so as to analyze the behavioral difference. With the results, we compare the quantitative measurement data with some previous qualitative analysis research on covert network. At last, we summarize the work.

2. Problem description

The topological characteristics of network derives from basic evolutionary behaviors [31]. In a dynamic organizational network, there are continuous addition and deletion of nodes with their links, as well as formation of links between existing nodes. As illustrated in Fig. 1, node addition is the behavior that a node joins in the network by connecting with existing nodes (as the red node A6 in Fig. 1); node deletion is that a node be removed along with its links (gray node A5); link formation is the process that existing nodes build links with each other (green link). These three behaviors can occur at the same time and affect the structure of network simultaneously. This is important because many real-world networks have all these behaviors. As in BA model, the attachment probability is precisely linear in the degree of the target node which results in a scale-free network. The objective of this paper is to measure the behavioral preference on various node properties in covert network and investigate how the property affects the preference.

Formally, an evolving covert network can be modeled as temporal sequential undirected networks $\{G(t)\}_{t\geq 1}$, with $V(t)$ and $E(t)$ represent the set of nodes and edges respectively. At each time t, $t \in [1, 2, \ldots, T]$, the network grows with $A(t)$ nodes and $M(t)$ edges. Simultaneously, $A'(t)$ nodes and $M'(t)$ edges are removed from the network. The number of links built between existing nodes at each time t is represented as $M''(t)$. Thus, we have

$$|V(t)| = |V(t-1)| + A(t) - A'(t), \quad (1)$$

$$|E(t)| = |E(t-1)| + M(t) - M'(t) + M''(t). \quad (2)$$

Here we assume that once a link is built, it will be exist all the time until one of the two ends is removed from the network. This is because, in a covert network, a relationship will exist until one of the individuals disappears (such as be arrested).