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Control Capacity and A Random Sampling Method in Exploring Controllability of Complex Networks

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Controlling complex systems is a fundamental challenge of network science. Recent advances indicate that control over the system can be achieved through a minimum driver node set (MDS). The existence of multiple MDS’s suggests that nodes do not participate in control equally, prompting us to quantify their participations. Here we introduce control capacity quantifying the likelihood that a node is a driver node. To efficiently measure this quantity, we develop a random sampling algorithm. This algorithm not only provides a statistical estimate of the control capacity, but also bridges the gap between multiple microscopic control configurations and macroscopic properties of the network under control. We demonstrate that the possibility of being a driver node decreases with a node’s in-degree and is independent of its out-degree. Given the inherent multiplicity of MDS’s, our findings offer tools to explore control in various complex systems.

The need to control is ubiquitous in many complex systems. For example, a cellular system controls a series of chemical reactions during its division to guarantee sufficient genetic materials in each daughter cell1–3. A company controls the dynamics of information flow for efficient task execution or innovation4. In a supply chain, cost is reduced by controlling the commodity flow5. Therefore there is an increasing need to understand the control principles of complex systems.

Recent advances in applying control theory6–8 to complex networks9,10 shed new light on this problem11–28. According to control theory, a dynamical system is controllable if it can be driven from any initial state to any desired final state within finite time6,7. Obviously, when we influence every element in the system, we obtain full control. However, control in general can be achieved through the control of only a subset of nodes that we call driver nodes. In a linear time-invariant system, the minimum driver node set (MDS) can be efficiently identified, representing the minimum set of nodes through which we can yield control over the whole system12. It has been shown that the number of driver nodes necessary for control (N_D) is fixed in a given network and primarily determined by the underlying degree distribution. Yet, there are often multiple control configurations with the same N_D24. For example, in the six-node network shown in Fig. 1a N_D = 4, but control can be achieved via five different MDS’s: {1, 2, 4, 6}, {1, 2, 4, 5}, {1, 2, 3, 6}, {1, 2, 3, 5} and {1, 2, 3, 4}.

The existence of multiple MDS’s indicates that not all nodes participate in control equiprobability, prompting us to quantify the role of each node in control. Here we introduce the concept of control capacity φ(i), defined as the fraction of MDS’s in which node i is included. This quantity measures the participation of node i in MDS’s, hence gives the likelihood that node i is a driver node when the network is under control via a random control configuration. For example, in Fig. 1a, the control capacity of each node is φ(1) = φ(2) = 1, φ(3) = φ(4) = 0.6 and φ(5) = φ(6) = 0.4. In connection with previous work that classifies nodes into three categories24, a node with φ = 1 is critical as it always acts as a driver node, φ = 0 is redundant as it never participates in MDS’s whereas 0 < φ < 1 is intermittent as it plays as a driver node in some control configurations but not all.

In spite of its direct relevance control capacity is difficult to measure, as only nodes with φ = 0 and φ = 1 can be identified in polynomial time24. Intuitively control capacity is readily obtained once all MDS’s are known. However, enumeration of all MDS’s in an arbitrary network is in the class of #P problem and computationally
prohibitive for large networks. Indeed, the number of MDS’s and can be typically biased. Based on these methods are not guaranteed to be uniform among randomly choose possible augmenting paths. However, sampling yields a MDS. One can use different algorithms to find the maximum matched set and node j in the in set in the bipartite graph (Fig. 1a, b). By performing the maximum matching in the bipartite graph12,30, the minimum driver nodes are unmatched nodes in the in set (Fig. 1c, d).

The method provides a direct connection between a maximum-matched set (MMS) and a MDS, as the complementary set of a MMS yields a MDS. One can use different algorithms to find the maximum matching in a bipartite graph, such as Hopcroft-Karp algorithm10, FordFulkerson algorithm31 and Hungarian algorithm32. All these algorithms aim to increase the matching size in each iteration via the augmenting path that starts at a matched node, end on an unmatched node and alternates between unmatched and matched links on the path17. Because there is no randomness in identifying an augmenting path, these algorithms will locate only one MMS for a given initial condition hence they are not appropriate for sampling purposes. Two simple modifications can be applied to bring randomness: one is to randomize the initial matching and the other is to randomly choose possible augmenting paths. However, sampling based on these methods are not guaranteed to be uniform among all MMS’s and can be typically biased.

Here we propose a novel algorithm that performs unbiased random sampling among all MMS’s, which equivalently samples all MDS’s and estimates the control capacity. The steps are as follows:

1. Obtain one MMS (denoted by M).
2. Randomly pick an element in M (denoted by node i).
3. Enumerate all alternative MMS’s that include all other elements of M except node i. (see Methods)
4. Randomly pick one of these alternative MMS as the current MMS M.
5. Repeat step 2.

Now we prove that the above steps randomly samples MMS’s. Considering each MMS as one state, our algorithm maps to a Markov chain characterized by a transition matrix P with the element 

\[ p_{ij} = \frac{1}{m(z+1)} \]

Similarly, from state j to i, the probability to pick element \( n_i \) out of m elements with probability \( 1/m \) and the pick of set M out of \( z+1 \) alternative sets with probability \( 1/(z+1) \). Therefore 

\[ p_{ij} = \frac{1}{m(z+1)} \]

Hence 

\[ p_{ij} = p_{ji} \]

and the transition matrix P is symmetric. For Markov chain with symmetric transition matrix, the steady state distribution is with equal probabilities for all states35. This means that in the long run, each MMS is picked with the same probability as all others.

To verify the result, we construct a small network with 244 MDS’s, perform our sampling algorithm 48,800 iterations and count the time that each MDS is picked. We find that each MDS is sampled approximately 200 times (Fig. 2a), which is the expected count a random sampling yields. The distribution of the counts follows a Gaussian distribution (Fig. 2b) centered at 200, implying the difference between actual and expected counts are due to random fluctuation.

One important attribute of a sampling method is the rate of convergence, capturing how fast the estimate converges to the actual value. Typically the rate of convergence is not known exactly unless an analytical solution can be found for the sampling process34. Via numerical tests, we find that the sampling results converges to the actual value after \( T = N \ln N \) iterations in a network with N nodes. The interpretation of T is intuitive: as our algorithm randomly draws the original elements in the MMS and replaces it with the new ones, the measure will not converge until we have the original MMS completely shuffled. Assuming that the size of the MMS is m, the expected number of iterations to obtain the first element replaced is 1, second element replaced is \( m(m-1) \) and the \( n^{th} \) element replaced is \( m! / (m-n)! \). Therefore for m elements the expected iteration is

\[
\sum_{i=0}^{m-1} \frac{m}{m-i} \ln m.
\]

As m varies but is proportional to network size N, we replace m by N and hence have the characteristic time-step T.

The characteristic time-step provides the minimum number of iterations necessary for sampling, therefore capturing the complexity in quantifying control capacity. The time needed to find one maximum matching can be as small as \( O(N^{0.5}) \) with the Hopcroft-Karp algorithm in a network with N nodes and L links36. To find one alternative MMS with one node replaced, a breadth first search is needed with \( O(L) \) time. As the number of alternative MMS is capped

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**Results**

**Random sampling algorithm.** We start by briefly reviewing the process in identifying \( N_D \) and MDS for an arbitrary directed network. First, a directed network is converted to a bipartite graph with two disjoint sets of nodes out and in. The out nodes can be considered as “superiors” that influence others internally. The in nodes are “subordinates” that need to be controlled. A directed link from node i to j corresponds to a connection between node i in the out set and node j in the in set in the bipartite graph (Fig. 1a, b). By performing the maximum matching in the bipartite graph12,30, the minimum driver nodes are unmatched nodes in the in set (Fig. 1c, d).

The method provides a direct connection between a maximum-matched set (MMS) and a MDS, as the complementary set of a MMS yields a MDS. One can use different algorithms to find the maximum matching in a bipartite graph, such as Hopcroft-Karp algorithm10, FordFulkerson algorithm31 and Hungarian algorithm32. All these algorithms aim to increase the matching size in each iteration via the augmenting path that starts at a matched node, end on an unmatched node and alternates between unmatched and matched links on the path17. Because there is no randomness in identifying an augmenting path, these algorithms will locate only one MMS for a given initial condition hence they are not appropriate for sampling purposes. Two simple modifications can be applied to bring randomness: one is to randomize the initial matching and the other is to randomly choose possible augmenting paths. However, sampling based on these methods are not guaranteed to be uniform among all MMS’s and can be typically biased.

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**Figure 1** | (a) An example of a directed network with six nodes. (b) The bipartite representation of the directed network in (a) where nodes are represented as two disjoint sets of nodes out and in. A directed link from node 1 to node 3 in (a) corresponds to a connection between node 1 in the out set and node 3 in the in set. (c) One maximum matching path (b) where one node can maximally match another node through one link. Colored nodes and links are matched nodes and links respectively. (d) One choice of minimum driver node set (MDS) to control the network based on the maximum matching in (c), i.e. controlling nodes 1, 2, 4 and 6 to control the whole system.

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by $N$, the complexity of one sampling is $O(NL)$. As the sampling time needed is proportional to $T$, the control capacity can be estimated in polynomial time as $O(N^2 L/\ln N)$.

To test our proposition, we construct a network with 100 nodes. We explicitly enumerate all 153,123 MDS’s (see Methods) and exactly measure the control capacity of all 33 nodes with $0 < \phi < 1$. Then we apply the random sampling and estimate the capacity $\phi(i)$ of each node $i$ at time-step $t$ based on the samples collected up to $t$ and $\phi^*(i)$ is the expected control capacity of node $i$ that is explicitly measured through the enumeration of all 153,123 MDS’s. Control capacity starts to converge at the characteristic time-step $T$. (d) The time evolution of the mean absolute percentage error MAPE = $\sum |\phi(i) - \phi^*(i)|/n$, where $n$ is the number of nodes with $0 < \phi < 1$. MAPE drops quickly after $T$ time-steps.

Control capacity in model and real networks. We check the relationship between a node’s topological property and its role in control. On the one hand, we find that a node’s out-degree does not affect its control capacity (Fig. 3b). This is because the outgoing links serve as means to control other nodes, which does not affect how this node itself would be controlled. On the other hand, control capacity does depend on in-degree. Particularly $\phi = 1$ when $k_{in} = 0$, indicating that nodes without incoming links need to be always controlled, in line with our previous finding\cite{24}. As in-degree increases, $\phi$ decays rapidly (Fig. 3a), indicating that a node with more incoming links is less likely to be a driver node.

Figure 2 | (a) The count on each of 244 MDS’s is around the expected value 200 when taking 48800 samples. (b) The distribution of the counts that is centered at 200 and can be well fitted by a Gaussian distribution. (c) The time evolution of $\phi(i)/\phi^*(i)$ of 33 nodes with $0 < \phi < 1$. $\phi(i)$ is the control capacity of node $i$ at time-step $t$ based on the samples collected up to $t$ and $\phi^*(i)$ is the expected control capacity of node $i$ that is explicitly measured through the enumeration of all 153,123 MDS’s. Control capacity starts to converge at the characteristic time-step $T$. (d) The time evolution of the mean absolute percentage error MAPE = $\sum |\phi(i) - \phi^*(i)|/n$, where $n$ is the number of nodes with $0 < \phi < 1$. MAPE drops quickly after $T$ time-steps.

Figure 3 | Dependency between control capacity $\phi$ and nodes’ in- and out-degree. (a) $\phi$ decays rapidly with in-degree $k_{in}$, suggesting that nodes with more incoming links are less likely to be a driver node. $\phi = 0$ when $k_{in} = 0$, indicating that nodes without incoming links are always driver nodes. (b) For the same networks in (a), $\phi$ does not vary with out-degree $k_{out}$, indicating control capacity is independent of out-degree. Networks analyzed are generated by static model (see Methods) with size $N = 10,000$ where $P(k_{in}) \sim k_{in}^{-\gamma_{in}}$, $P(k_{out}) \sim k_{out}^{-\gamma_{out}}$, $\gamma_{in} = \gamma_{out} = \gamma$ and $\langle k_{in} \rangle = \langle k_{out} \rangle = \frac{1}{2} \langle k \rangle$. 

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incoming links are less likely to be a driver node as they are more likely to be influenced internally.

We extend the analysis to real systems and check the relationship between \( \langle k_i \rangle \) and \( \langle k \rangle \), which are the average degree of the driver nodes and all nodes, respectively (Table 1). With control capacity, \( \langle k_i \rangle \) can be explicitly expressed as \( \langle k_i \rangle = \frac{\sum_k \phi(k)}{N} \) where \( k \) is the degree of an arbitrary node \( i \). One would expect \( \langle k_i \rangle < \langle k \rangle \) in real networks since \( \phi \) decreases with \( k \). However, while the fact that the average in-degree of driver nodes is less than that of the network \( \langle k_{D,in} \rangle < \langle k \rangle \) reflects the relationship between \( \phi \) and \( k_{D,in} \), average out-degree of driver nodes \( \langle k_{D,out} \rangle \) can be affected by the in- and out-degree correlation \( \langle k_{D,in} \rangle > \langle k_{D,out} \rangle \). Indeed several networks are found with \( \langle k_{D,out} \rangle > \langle k_{D,out} \rangle \) (e.g. Seagrass in food web and TRN-Yeast-2 in regulatory networks of Table 1) and in one network we even observe that \( \langle k_1 \rangle \) is slightly higher than \( \langle k \rangle \) (TRN-EC-2 in regulatory networks of Table 1). But for majority of real networks the average degree of driver nodes are less than that of the whole network, leading to the conclusion that hubs are less likely to be driver nodes.

Finally, we check how control capacity is distributed among nodes with \( 0 < \phi < 1 \) in Erdös-Rényi networks, scale-free networks (see Methods) and some real networks (Fig. 4). The distributions are found to depend on specific network configurations and there seems no simple universal function for the distribution. As a common feature, \( \phi \) typically displays multi-modal distribution, implying that several clusters of nodes share the same chance of being driver nodes. Recent work discovered that dense networks with identical degree distribution can stay in one of the two control modes, centralized or distributed, depending on the fraction of nodes that can participate in MDS’s. The distributions of control capacity corresponding to networks in the two control modes also show distinct features. For networks in distributed mode, a significant fraction of nodes are with control capacity close to zero (Fig. 4(b), (e)). This indicates that while many nodes can participate in MDS’s, their participation is not frequent compared with the huge number of MDS’s in distributed mode. For networks in centralized mode, the number of nodes with \( 0 < \phi < 1 \) is small, but the distribution of capacity among these nodes is similar to that when \( \langle k \rangle \) is small (Fig. 4(c), (f)).

**Discussion**

In summary, uncovering the role of individual nodes in controlling a network requires us to understand control capacity, a centrality measure quantifying a node’s likelihood of being a driver node. While a network’s control can be achieved via different MDS’s and each may give rise to different outcomes, we lack a tool to average the effect of different MDS’s or statistically analyze the consequences driven by different MDS’s over the network. In this paper we propose a random sampling algorithm, allowing us to efficiently measure control capacity in arbitrary networks. The proposed algorithm bridges the gap between multiple microscopic control configurations and macroscopic properties of the network under control. One important example of its application is the study of \( \langle k_1 \rangle \), which can not be properly addressed without the random sampling method.

The results presented have many potential applications in future works. For example, recent work on the controllability of bank systems investigated the time correlation of nodes’ roles in control. The measure of control capacity could be crucial in such tasks, especially in temporal networks where a node’s role in control varies with time. The relationship between control capacity and the efficiency or energy cost in control are also important issues for further investigations. The random sampling method is useful in problems when an overall measure of a network is needed. As an example, when estimating the control robustness of a network, the random sampling algorithm has to be considered as different MDS’s may facing different failure risks. Finally, links do not participate in control in an equal manner, allowing multiple link combinations to spread the control signal. Our approach can offer insights for future work exploring the participation of links in control. Given the inherent multiplicity feature in control, our findings offer fundamental tools to explore control in various complex systems.

**Methods**

Enumerating all alternative MMS’s with one node replaced. Suppose the maximum matching is obtained in a bipartite graph and denote \( M \) by the current maximally-matched set (MMS) of nodes in the in set. Assume node \( i \) is an element of the set \( M \).
The following procedures can provide all MMS’s that contain all other elements of $M$ except node $i$. (0) Set node $i$ as the removal node. (1) Identify the node in the out set that matches the removal node (denoted by node $j$). (2) Keep the current matched nodes and links unchanged, remove the removal node with all its links. (3) Check if there is an augmenting path that starts from node $j$, ends at an unmatched node and alternates between unmatched and matched links on the path. (4) If so, we obtain a new MMS with node $i$ replaced. Update the matched links and nodes correspondingly. Set the new matched node in the in set as the removal node and repeat step (1). (5) If not, there is no new MMS with node $i$ replaced and all of them are enumerated already.

Enumerating all MDS’s. For a given bipartite graph, we first remove all the always matched nodes in the in set and their links (algorithm discussed in reference 24). Define $S_i$ as a set of nodes that a out node $i$ can reach. For example, in Fig. 1b there are $S_1 = \{3, 4, 5, 6\}$ and $S_2 = \{5, 6\}$. Effectively $S_i$ is the set of nodes that node $i$ can match. In the bipartite graph with no always matched nodes in the in set, a MMS of $i$ nodes is a set of nodes without duplication, each drawn from one set $S_i$. Therefore, we can repeatedly test all possible combinations to enumerate all MMS’s that equivalently provides all MDS’s. Note that nodes chosen from different $S_i$’s can sometimes give rise to the same MMS. For example, in Fig. 1b picking node 5 from $S_1$ and node 6 from $S_2$ yields the same MMS as picking node 6 from $S_1$ and node 5 from $S_2$. All MMS’s need to be recorded. Once a valid node combination is found, it needs to be checked with previously found MMS to avoid double count.

Generating a scale free network. The scale-free networks analyzed are generated via the static model. We start from $N$ disconnected nodes indexed by integer number $i (i = 1, \ldots, N)$. The weight $w_{\text{out},i}$ and $w_{\text{in},j}$ is assigned to each node in the out and the in set, with probability proportional to $w_{\text{out},i}$ and $w_{\text{in},j}$. Connect node $i$ and $j$ if there is no connection between them, corresponding to a directed link from node $i$ to node $j$ in the digraph. Otherwise randomly choose another pair. Repeated the procedure until $\sum_{i=1}^{N} w_{\text{out},i}$ links are created. The degree distribution under this construction is $P(k) \sim k^{1 - a_{\text{out}} - a_{\text{in}}}$ in the large $k$ limit.

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