Title:	Echo in complex networks
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Abstract:	Large populations of globally coupled or uncoupled oscillators have been recently shown to exhibit an intriguing echo behavior [Ott, Platig, Antonsen, and Girvan, Chaos: An Interdiscip. J. Nonlinear Sci. 18, 037115 (2008); Chen, Tinsley, Ott, and Showalter, Phys. Rev. X 6, 041054 (2016)], wherein a system is perturbed by two successive pulses at times T and T + τ inducing a spontaneous increase in the order parameter at the given times. These two provoked increments in the order parameter are followed by an unprovoked spontaneous increment in the order parameter at time T + 2 τ termed as an echo. In this paper, the effects of network topology on the emergence of an echo are explored. Two principal network parameters, namely, average degree and network randomness, are varied for this purpose. The networks are rewired to increase randomness in the network connections using the Watts-Strogatz algorithm to generate small world networks [Watts and Strogatz, Nature (London) 393, 440 (1998)]. Thus, the whole span of networks ranging from a regular ring to a completely random network is explored. The average degree of the underlying connectivity, starting from nearest neighbor connections, is also monotonically increased and its effects on the echo behavior are analyzed. We find that for rings with low average degrees and high coupling strengths a discernible echo is not observed. Remarkably, an echo reemerges in the presence of sufficient randomness in the connections for such networks. For a regular ring network, increasing the average degree after a critical value also yields a transition to echo behavior. However, for completely random networks echoes are present in networks of all average degrees. This suggests that randomizing connections can induce echoes in systems even when the average degree of connections is very low. Another subtle feature arises for intermediate randomness, where the system exhibits a nonmonotonic dependence of the echo size on average degree. The echo size was found to be minimum at an intermediate value of the average degree. Lastly we consider the influence of dynamically changing links on the echo size and demonstrate that time-varying connections destroy the echo in low average degree networks, while the echo persists under dynamic links in high average degree networks. So our results clearly demarcate the class of networks that are robust candidates for exhibiting echoes, as well as provide caveats for the observation of echoes in networks.
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