REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01/24/2018	Final Report	09/05/12-9/30/17

4. TITLE AND SUBTITLE
Distributed Synchronization in Communication Networks

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-16-1-2150

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Tang, Ao Kevin

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cornell University
373 Pine Tree Rd, EHP
Ithaca NY 14850-2820

8. PERFORMING ORGANIZATION REPORT NUMBER
Cornell OSP 68635

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research (ONR)
875 N Randolph St Suite 1425
Arlington VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
NAVY-ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release: Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The major goals of this project include two components: First, to broaden and deepen the fundamental understanding of coupled oscillators systems by relaxing the standard restrictive assumptions on topology (whom to connect), coupling (how to connect) and delay (when to connect). A better understanding of these factors is needed in order to predict the behavior of the system. The second part is on the impact of this project to DoD capabilities via distributed synchronization and scheduling protocol design. Both goals have been successfully met.

15. SUBJECT TERMS
Networking, Synchronization

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Ao Kevin Tang
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU		607-255-4803

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final Technical Report for "Distributed Synchronization in Communication Networks" (N00014-16-1-2150)

PI: Ao Kevin Tang
Institution: Cornell University

Abstract:

Despite many different types of such networks, the need for coordination among mobile agents is ubiquitous. Coordination is needed in order to perform time consistent measurements to track targets, to communicate between different agents in the network without interfering one another, and to set up awake communication periods that overlap enough in order to save energy and keep connectivity. Underlying all these is the fundamental requirement to achieve synchronization, in a distributed manner. This is however a daunting task given all the possible (and ever changing) network topology and varying delay among agents.

In this project, we focus on a class of powerful models with many merits including energy efficiency and convergence time, the models of coupled oscillators. The major goals of this project include two components: First, to broaden and deepen the fundamental understanding of such systems by relaxing the standard restrictive assumptions on topology (whom to connect), coupling (how to connect) and delay (when to connect). A better understanding of these factors is needed in order to predict the behavior of the system. The second part is on the impact of this project to DoD capabilities via distributed synchronization and scheduling protocol design.

Both goals have been successfully met. More concretely, for goal number 1, we have provided a sufficient condition that can be used to check equilibrium stability. We have also shown that a system of delayed coupled oscillators can be approximated by a non-delayed one whose coupling depends on the delay distribution. This shows how the stability properties of the system depend on the delay distribution and allows us to predict its behavior. For goal number 2, based on our understanding of coupled oscillators, we have developed a skewless network clock synchronization without discontinuity. We analyzed its convergence and performance and tested it with a real physical testbed.

1. Overall Goals and Achievements

Despite many diffierent types of such networks, the need for coordination among mobile agents is ubiquitous. Coordination is needed in order to perform time consistent measurements to track targets, to communicate between different agents in the network without interfering one another, and to set up awake communication periods that overlap enough in order to save energy and keep connectivity. Underlying all these is the fundamental requirement to achieve synchronization, in a distributed manner. This is however a daunting task given all the possible (and ever changing) network topology and varying delay among agents.

In this project, we focus on a class of powerful models with many merits including energy efficiency and convergence time, the models of coupled oscillators. The major goals of this project include two components: First, to broaden and deepen the fundamental understanding of such systems by relaxing the standard restrictive assumptions on topology (whom to connect), coupling (how to connect) and delay (when to connect). A better understanding of these factors is needed in order to predict the behavior of the system. The second part is on the impact of this project to DoD capabilities via distributed synchronization and scheduling protocol design.

Both goals have been successfully met. More concretely, for goal number one, we have provided a sufficient condition that can be used to check equilibrium stability. We have also shown that a system of delayed coupled oscillators can be approximated by a non-delayed one whose coupling depends on the delay distribution. This shows how the stability properties of the system depend on the delay distribution and allows us to predict its behavior. For goal number two, based on our understanding of coupled oscillators, we have developed a skewless network clock synchronization without discontinuity. We analyzed its convergence and performance and tested it with a real physical testbed.

2. Description of Topics and Results

Synchronization of Weakly Coupled Oscillators

There are three key factors in a system of coupled oscillators that characterize the interaction between them: coupling (how to affect), delay (when to affect) and topology (whom to affect). The existing work on each of these factors has mainly focused on special cases. With new angles and tools, we make progress in relaxing some assumptions on these factors. There are three main results in this paper. Firstly, by using results from algebraic graph theory, a sufficient condition is obtained that can be used to check equilibrium stability. This condition works for arbitrary topology, generalizing existing results and also leading to a sufficient condition on the coupling function which guarantees that the system will reach synchronization. Secondly, it is known that identical oscillators with sin() coupling functions are guaranteed to synchronize in phase on a complete graph. Our results prove that in many cases certain structures such as symmetry and concavity, rather than the exact shape of the coupling function, are the keys for global synchronization. Finally, the effect of heterogeneous delays is investigated. Using mean field theory, a system of delayed coupled oscillators is approximated by a non-delayed one whose coupling depends on the delay distribution. This shows how the stability properties of the system depend on the delay distribution and allows us to predict its behavior. In particular, we show that for sin() coupling, heterogeneous delays are equivalent to homogeneous delays. Furthermore, we can use our novel sufficient instability condition to show that heterogeneity, i.e. wider delay distribution, can help reach in-phase synchronization.

Skewless Network Clock Synchronization Without Discontinuity

We examine synchronization of computer clocks connected via a data network and proposes a skewless algorithm to synchronize them. Unlike existing solutions, which either estimate and compensate the frequency difference (skew) among clocks or introduce offset corrections that can generate jitter and possibly even backward jumps, our solution achieves synchronization without these problems. We first analyze the convergence property of the algorithm and provide explicit necessary and sufficient conditions on the parameters to guarantee synchronization. We then study the effect of noisy measurements (jitter) and frequency drift (wander) on the offsets and synchronization frequency, and further optimize the parameter values to minimize their variance. Our study reveals a few insights, for example, we show that our algorithm can converge even in the presence of timing loops and noise, provided that there is a well-defined leader. This marks a clear contrast with current standards such as NTP and PTP, where timing loops are specifically avoided. Furthermore, timing loops can even be beneficial in our scheme as it is demonstrated that highly connected subnetworks can collectively outperform individual clients when the time source has large jitter. The results are supported by experiments running on a cluster of IBM BladeCenter servers with Linux.

Distributed Synchronization of Heterogeneous Oscillators on Networks With Arbitrary Topology

Many network applications rely on the synchronization of coupled oscillators. For example, such synchronization can provide networked devices with a common temporal reference necessary for coordinating actions or decoding transmitted messages. We study the problem of using distributed control to achieve phase and frequency synchronization of a network of coupled heterogeneous nonlinear oscillators. Not only do our controllers guarantee zero-phase error in steady state under arbitrary frequency heterogeneity, but they also require little knowledge of the oscillator nonlinearities and network topology. Furthermore, we provide a global convergence analysis, in the absence of noise and propagation delay, for the resulting nonlinear system whose phase vector evolves on the n-torus.

Phase-Coupled Oscillators with Plastic Coupling

We study synchronization of systems of homogeneous phase-coupled oscillators with plastic coupling strengths and arbitrary underlying topology. The dynamics of the coupling strength between two oscillators is governed by the phase difference between these oscillators. We show that, under mild assumptions, such systems are gradient systems, and always achieve frequency synchronization. Furthermore, we provide sufficient stability and instability conditions that are based on results from algebraic graph theory. For a special case when underlying topology is a tree, we formulate a criterion (necessary and sufficient condition) of stability of equilibria. For both, tree and arbitrary topologies, we provide sufficient conditions for phase-locking, i.e., convergence to a stable equilibrium almost surely. We additionally find conditions when the system possesses a unique stable equilibrium, and thus, almost global stability follows. Several examples are used to demonstrate variety of equilibria the system has, their dependence on system's parameters, and to illustrate differences in behavior of systems with constant and plastic coupling strengths.

3. Student Training

Several results from this project have been included in a graduate course (ECE 5800: Control and Optimization of Information Networks) at Cornell. The grant also partially supported five PhD students (Enrique Mallada, Nithin Michael, Chiunlin Lim, Andrey Gushchin, Ning Wu). Enrique graduated in 2014 and is a now a tenure-track assistant professor at Johns Hopkins University. Chiunlin Lim graduated in 2014 and is now with Facebook Inc. Nithin Michael graduated in 2015 and is with Waltz Networks Inc. Andrey Gushchin graduated in 2016 and is with Waltz Networks Inc. Ning Wu will graduate in Fall of 2018.

4. Results Dissemination

In terms of publications, we have published most related results, including five Conference papers and four journal papers. In terms of talks, besides several conference presentations, we have also given several invited seminars at various places including Berkeley, Stanford, AT&T Labs and Bell Labs.

5. Future Direction

One of my future directions is to study high frequency traffic management in computer networks. It will be a critical technology to truly realize a flexible high performance network. One key ingredient of that technology is the ability to synchronize agents accurately and quickly. The results from the current project should serve as an excellent basis for my new endeavor.

6. Main Related Publication

[1] A. Gushchin, E. Mallada and A. Tang, "Synchronization of Heterogeneous Kuramoto Oscillators with Arbitrary Topology", Proceedings of ACC, 2015

[2] A. Gushchin, E. Mallada and A. Tang, "Synchronization of Heterogeneous Kuramoto Oscillators with Graphs of Diameter Two", Proceedings of CISS, 2015

[3] A. Gushchin, E. Mallada and A. Tang, "Synchronization of Phase-coupled Oscillators with Plastic Coupling Strength", (invited) Proceedings of ITA workshop, 2015

[4] N. Wu, Y. Bi, N. Michael, A. Tang, J. Doyle and N. Matni, "HFTraC: High-Frequency Traffic Control", Proceedings of ACM Sigmetrics, 2017.

[5] A. Gushchin, E. Mallada and A. Tang, "Phase-coupled Oscillators with Plastic Coupling: Synchronization and Stability", *IEEE Transactions on Network Science and Engineering*, 3(4): 240-256, October-December, 2016.

[6] E. Mallada, R. Freeman and A. Tang, "Decentralized Synchronization of Heterogeneous Oscillators on Networks with Arbitrary Topology", *IEEE Transactions on Control of Networked Systems*, 3(1): 12-23, March 2016.

[7] E. Mallada, X. Meng, M. Hack, L. Zhang and A. Tang, "Skewless Network Clock Synchronization Without Discontinuity: Convergence and Performance", *IEEE/ACM Transactions on Networking*, 23(5): 1619-1633, October 2015.

[8] E. Mallada and A. Tang, "Synchronization of Weakly Coupled Oscillators: Coupling, Delay and Topology", J. Phys. A: Math. Theor. 46(2013) 505101, December 2013.

[9] E. Mallada, X. Meng, M. Hack, L. Zhang and A. Tang," Skewless Network Clock Synchronization", Proceedings of IEEE ICNP, 2013