Asynchronous Consensus Protocols: Preliminary Results, Simulations and Open Questions

Lei Fang, Panos J. Antsaklis, and Anastasis Tzimas

***Abstract*— Consensus is well accepted as being a fundamental paradigm for coordination of groups of autonomous agents. Recently, we casted previous work on multi-agent consensus protocols into an asynchronous framework, where each agent updates on its own pace, and uses the most recently received information from other agents. Asynchronous consensus protocols encompass those synchronous ones with various communication patterns. In this paper, we study via simulation a number of open new problems introduced by the asynchronous operation of multi-agent systems. More interestingly, the existing consensus results are classified by their communication assumptions and future research directions are proposed. To facilitate our study, we develop a multi-vehicle simulator in Java, built on top of JProwler; JProwler is a discrete event simulator for prototyping, verifying and analyzing communication protocols of ad-hoc wireless networks. Implementation issues with their implications are also discussed.**

I. INTRODUCTION

Consensus has been recognized as being of great importance in coordinating groups of autonomous agents [2], [9], [14], [22], [23]. A consensus protocol provides means through which all agents agree on some particular variable of interest. This variable can be given different interpretations depending on the application. It can present the attitude alignment in multiple spacecraft setting, heading direction in flocking, group average in distributed computation, steady state in Markov chains, time-on-target in cooperative attack, etc. This shared variable or information is a necessary condition for cooperation in multi-agent systems, as shown in [25]. The challenge here is for the group to have a consistent view of the coordination variable in the presence of unreliable, dynamically changing communication topology (without global information exchange).

A number of researchers have addressed the multi-agent consensus problem under the information constraints in different settings. The work in [9] focuses on attitude alignment on undirected graphs. It is shown that the consensus on the heading angles of the agents can be achieved if the union of the interaction graphs for the team are connected frequently enough as the system evolves. Average-consensus problem is solved in [22] over strongly connected and balanced digraphs. Ren *et al.* [23] extend the results of [9] from the bidirectional case to unidirectional case. If the union of the collection of interaction graphs across some time interval had a spanning tree frequently enough, consensus (not necessarily average-consensus) can still be achieved. In [21], tools from nonlinear dynamics are used to obtain a broad class of communication patterns that guarantee global consensus. Other recent results on consensus problems include [1], [2], [5], [8], [12], [14], [18], [27], [28], [31], to name a few. See also [6], [26] for a review on consensus problems in multi-agent coordination.

The aforementioned consensus protocols all operate in a synchronized fashion since each agent's decisions must be synchronized to a common clock shared by all other agents in the group. This synchronization requirement might not be natural in certain contexts. For example, the agreement of time-on-target in cooperative attack among a group of UAVs depends in turn on the timing of when to exchange and update the local information. This difficulty entails the consideration of the asynchronous consensus problem, where each agent updates on its own pace, and uses the most recently received (but possibly outdated) information from other agents. No assumption is made about the relative speeds and phases of different clocks. Agents communicate solely by sending messages, however there is no guarantee on the time of delivery or even of a successful delivery. Therefore, heterogeneous agents, time-varying communication delays and packet dropout can all be taken into account in the same framework. Nevertheless, the asynchronism can destroy convergence properties that the algorithm may possess when executed synchronously or sequentially. Thus, the analysis of asynchronous algorithms is more difficult than that of their synchronous counterparts. We refer readers to [4], [7], [11] for surveys on general theory of asynchronous systems.

Work reported on asynchronous consensus problems is relatively sparse compared to its synchronous counterparts. A distributed iterative procedure under a weak form of asynchronism (called virtual synchronization) is developed by Mehyar *et. al* for calculating averages over an unstructured peer-to-peer network [18]. Recently, we introduced an asynchronous framework to study the consensus problems for discrete-time multi-agent systems [6]. By combining linear asynchronous, graph and matrix theories with a decomposition scheme, we prove, under a fixed information topology, the discrete-time asynchronous protocol achieves consensus asymptotically if the information exchange topology has a spanning tree. The most attractive aspects of this development is the fact that once the stability result was established for asynchronous protocols, the stability for synchronous protocols under dynamically changing interaction topologies

L. Fang, P. J. Antsaklis and Anastasis Tzimas are with Dept. of Electrical Engineering, Univ. of Notre Dame, Notre Dame, IN 46556. E-mail: {lfang,antsaklis.1}@nd.edu. This work was partially supported by the Center for Applied Mathematics, Univ. of Notre Dame.

is immediate since it can be seen as a special case of the asynchronous protocol with zero communication delays. Our asynchronous result extends the existing (synchronous) results reported in [9], [18], [21]–[23]. For other related problems in asynchronous multi-agent systems, see [3], [13], [15]–[17], [30].

The asynchronism gives a new dimension to the consensus problems. In this work, we examine via simulation a number of open new problems that arise from the asynchronous operation of multi-agent systems. In particular, we examine how asynchronous consensus value, delay and updating sets, imperfect communication channels, and communication topology affect (or are affected by) the consensus convergence process. Furthermore, the existing consensus results are classified by their communication assumptions and future research directions are pointed out. To facilitate our study, we develop a multi-vehicle simulator in Java, built on top of JProwler; JProwler is a discrete event simulator for prototyping, verifying and analyzing communication protocols of ad-hoc wireless networks [10]. Implementation issues with their implications are also discussed. The main purpose of this paper is to provide an asynchronous view to consensus problems in the cooperative control community with the goal to facilitate research along this new direction.

II. Preliminaries and Background

A. Definitions and Notations

Let $G=\{V,E,A\}$ be a weighted digraph (or direct graph) of order n with the set of nodes $V=\{v_1,v_2,\ldots,v_n\}$, set of edges $E\subseteq V\times V$, and a weighted adjacency matrix $A=[a_{ij}]$ with nonnegative adjacency elements a_{ij}. The node indices belong to a finite index set $\mathscr{I}=\{1,2,\ldots,n\}$. A directed edge of G is denoted by $e_{ij}=(v_i,v_j)$. For a digraph, $e_{ij}\in E$ does not imply $e_{ji}\in E$. The adjacency elements associated with the edges of the graph are positive, i.e., $a_{ij}>0$ if and only if $e_{ji}\in E$. Moreover, we assume $a_{ii}\neq 0$ for all $i\in\mathscr{I}$. The set of neighbors of node v_i is the set of all nodes which point (communicate) to v_i, denoted by $N_i=\{v_j\in V:(v_j,v_i)\in E\}$.

A digraph G can be used to model the interaction topology among a group of agents, where every graph node corresponds to an agent and a directed edge e_{ij} represents a unidirectional information exchange link from v_i to v_j, that is, agent j can receive information from agent i. The interaction graph represents the communication pattern at certain time. The interaction graph is time-dependent since the information flow among agents may be dynamically changing. Let $\bar{G}=\{G_1,G_2,\ldots,G_M\}$ denote the set of all possible interaction graphs defined for a group of agents. Note that the cardinality of $\bar{G}$ is finite. The union of a collection of graphs $\{G_{i_1},G_{i_2},\ldots,G_{i_m}\}$, each with vertex set V, is a graph $\mathbb{G}$ with vertex set V and edge set equal to the union of the edge sets of $G_{i_j},\ j=1,\ldots,m$.

A directed path in graph G is a sequence of edges $e_{i_1i_2}$, $e_{i_2i_3}$, $e_{i_3i_4}$, $\cdots$ in that graph. Graph G is called strongly connected if there is a directed path from v_i to v_j and v_j to v_i between any pair of distinct vertices v_i and v_j. Vertex v_i is said to be linked to vertex v_j across a time interval if there exists a directed path from v_i to v_j in the union of interaction graphs in that interval. A directed tree is a directed graph where every node except the root has exactly one parent. A spanning tree of a directed graph is a tree formed by graph edges that connect all the vertices of the graph.

Let $x_i\in\mathbb{R}$, $i\in\mathscr{I}$ represent the state associated with agent i. A group of agents is said to achieve global consensus asymptotically if for any $x_i(0)$, $i\in\mathscr{I}$, $\|x_i(t)-x_j(t)\|\to 0$ as $t\to\infty$ for each $(i,j)\in\mathscr{I}$. Besides being of interest in its own right, if consensus is attainable (all agents converge to a common point), then other formations are achievable too [14]. So the focus is on convergence to a point.

Let $\mathbf{1}$ denote an $n\times 1$ column vector with all entries equal to 1. Let $M_n(\mathbb{R})$ represent the set of all $n\times n$ real matrices. A matrix $F\in M_n(\mathbb{R})$ is nonnegative, $F\geq 0$, if all its entries are nonnegative, and it is irreducible if and only if $(I+|F|)^{n-1}>0$. Furthermore, if all its row sums are $+1$, F is said to be a (row) stochastic matrix.

B. Synchronous and Asynchronous Consensus Protocols

We consider the following (synchronous) discrete-time consensus protocol [19], [22], [23]

$$x_i(t+1)=\frac{1}{\sum_{j=1}^{n}A_{ij}(t)}\sum_{j=1}^{n}A_{ij}(t)x_j(t) \qquad (1)$$

where $t\in\{0,1,2,\cdots\}$ is the discrete-time index, $(i,j)\in\mathscr{I}$ and $A_{ij}(t)>0$ if information flows from v_j to v_i at time t and zero otherwise, $\forall j\neq i$. The magnitude of $A_{ij}(t)$ represents possibly time-varying relative confidence of agent i in the information state of agent j at time t or the relative reliabilities of information exchange links between them. We can rewrite (1) in a compact form

$$x(t+1)=F(t)x(t) \qquad (2)$$

where $x=[x_1,\cdots,x_n]^T$, $F=F_{ij}$ with $F_{ij}=\frac{A_{ij}(t)}{\sum_{j=1}^{n}A_{ij}(t)}$, $(i,j)\in\mathscr{I}$. An immediate observation is that the matrix F is a nonnegative stochastic matrix, which has an eigenvalue at 1 with the corresponding eigenvalue vector equal to $\mathbf{1}$.

The protocol (1) or (2) is localized since the state of agent v_i only depends on the states of itself and its neighbors. Furthermore, this protocol is and synchronous in the sense that all the agents update their states at the same time using the latest values of neighbors' states.

On the other hand, in the asynchronous setting the order in which states of agents are updated is not fixed and the selection of previous values of the states used in the updates is also not fixed. Now let $t_0<t_1<\cdots<t_n<\cdots$ be the time instants when the state of the multi-agent system undergoes change. Let $x_i(k)$ denote the state of agent i at time t_k. The index k is also called the event-based discrete time index in the literature. The dynamics of asynchronous systems can be written as

$$x_i(k+1)=\begin{cases}\sum_{j=1}^{n}F_{ij}(k)x_j(k-d(i,j,k)) & \text{if } i\in S(k),\\ x_i(k) & \text{otherwise,}\end{cases} \qquad (3)$$

where $d(i,j,k) \geq 0$ are nonnegative integers, $S(k)$ are non-empty subsets of $\{1,\cdots,n\}$, the initial states are specified by $x(0) = x(-1) = \cdots$ Henceforth, we write the initial vector $x(0)$ to abbreviate reference to this set of equal initial states. We refer to the $d(i,j,k)$ as iteration delays and $S(k)$ as updating sets. The following assumption (called *regularity assumption*) is usually made in the study of linear asynchronous linear systems.

- There exists a nonnegative integer D such that

$$0 \leq d(i,j,k) \leq D < \infty, \; \forall\, (i,j,k). \tag{4}$$

  Condition (4) indicates that only a finite number of updating instants can occur within any time interval of finite length. In the literature, this is also called partially asynchronism or (uniformly) bounded-delay asynchronism.
- The updating sets $S(k)$ satisfy

$$\bigcup_{k=K}^{\infty} S(k) = \{1,\cdots,n\}, \text{ for any } K. \tag{5}$$

  Condition (5) says that every agent is updated infinitely often. In other words, no agent fails to be updated as time goes on.

C. Convergence Results

In this section, we review convergence results for synchronous and asynchronous consensus protocols under a (structurally) fixed topology. Both synchronous and asynchronous cases requires that the interaction matrix F has a directed spanning tree in the associated interaction graph G.

Theorem 1 ([24]) *Given the synchronous protocol (1) with $F(k) = F$, $\forall k \in \mathbb{N}$, the consensus is asymptotically reachable if and only if the associated interaction graph G has a spanning tree. That is, global consensus is asymptotically reachable.*

Theorem 2 ([6]) *Consider the asynchronous protocol (3) with structurally fixed topology $F(k) = F$, $\forall k \in \mathbb{N}$. Assume that all the agents can access their own states (i.e., F has positive diagonal entries) and at least one of the agents can access its own state without delay and the initial value is great than zero. Then the consensus is asymptotically reachable if the associated (directed) graph G has a spanning tree. That is, global consensus is asymptotically reachable under the asynchronous mode.*

Remark 1 *The convergence process of asynchronous protocol (3) is fundamentally different from that of the synchronous protocol (1). In the synchronous case, $x(t)$ converges to a consensus point, which is only a function of the interaction topology and initial states and otherwise independent of the computations; In the latter case, $x(k)$ converges to a consensus point depending on the computations, that is, on the update sets, the delays, and initial states.*

The following theorem is obtained by several authors [6], [19], [23] via different approaches.

Theorem 3 *Let $G(t) \in \bar{G}$ be a time-varying interaction graph at time t, with the weights selected from a finite set of arbitrary positive numbers. The protocol (3) achieves global consensus asymptotically if and only if there exists an infinite sequence of contiguous, nonempty, bounded time intervals $[t_l, t_{l+1})$, $l \geq 0$, starting at $t_0 = 0$, with the property that across each such interval, the union of the interaction graphs has a spanning tree.*

III. Simulation Results and Open Questions

In the asynchronous framework, we examine how asynchronous consensus value, delay and updating sets, imperfect communication channels, and communication topology affect (or are affected by) the consensus convergence process. To be more concrete, we use as a baseline example a multi-agent system with six agents and a (structurally fixed and equally weighted) interaction topology as shown in Fig. 1. A number of simulation results are presented and open questions are raised. Notice that these results and questions are quite generic and not limited to the system under study.

A. Asynchronous Consensus Value

This part shows that the asynchronous consensus value generally depends on the course of the computations. Since the interaction graph has a directed spanning tree, the consensus is reachable in the asynchronous mode. The system is always started with the same initial condition $x(0) = [0.94\;\; -0.90\;\; -0.68\;\; 0.85\;\; -0.41\;\; -0.71]^T$ for easy comparison. At every iteration, a node is chosen to update its state randomly and independently of other nodes with probability p. The delay $d(i,j,k)$ in (3) is a discrete random variable taking an integer value between 0 and D with an equal probability. In the simulations, all randomizations across the nodes and across the iterates are independent .

Fig. 2 shows different consensus values for 2000 Monte Carlo runs with node selection probability $p = 1/2$ and the delay bound $D = 0$ (zero-asynchronism). From this figure, while the synchronous consensus value depends only on the initial condition once the interaction topology is given, it is clear that the asynchronous consensus value can take any value in a bounded range (a rough estimate is given by $[\min_i x_i(0), \max_i x_i(0)]$), . Interestingly, the mean of the asynchronous consensus values is very close to the synchronous consensus value of -0.085.

B. Delay and Updating Sets

The effects of the magnitudes of the node selection probability p and the delay bound D on the consensus dynamics are explored. On one hand, the asynchronous systems tend to behave more like synchronous systems with increasing p (for fixed topology F and delay bound D). As expected, this effect is less noticeable when D becomes large. On the other hand, one may expect that decreasing D (with fixed p) has a similar effect on asynchronous systems as increasing p. However,

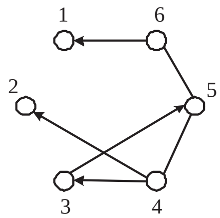


Fig. 1. The interaction topology of an asynchronous multi-agent system.

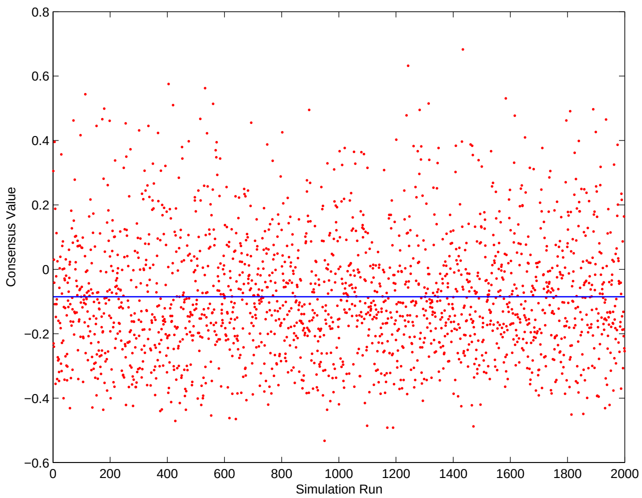


Fig. 2. Asynchronous consensus value ($p = 1/2$ and $D = 0$) depends on various topology selections made in the course of the computations (Horizontal line shows the synchronous consensus value).

this turns out to be false. The histogram of consensus value with a large delay bound $D = 8$ (2000 simulation runs) is shown in Fig. 3(c). It can be seen that the consensus region instead shrinks by more than 40% compared to the zero asynchronism case Fig. 3(a).

Under zero asynchronism, the consensus is reached in shorter time compared to that of the long delay case as shown in Figs. 3(b) and 3(d). A fast consensus convergence process is not always desirable since a slow convergence process may result in a smaller region for the final consensus value. This leads to the first open question:

Q1: What is the effect of p and D on the consensus convergence process? This problem is meaningful since we may have some prior knowledge about p and D. Does a deterministic updating scheme exist that would allow the control of the consensus value?

C. Communication/Sensor Noise

In practice, the agent state may be corrupted by noise due to defective sensors or unreliable information exchange. For synchronous consensus protocols, explicit upper bounds for the inconsistency (absolute difference) between agent state when there exist bounded noise are given via an input-to-state analysis [24]. This analysis, however, cannot be directly adapted to the asynchronous case due to the fact that

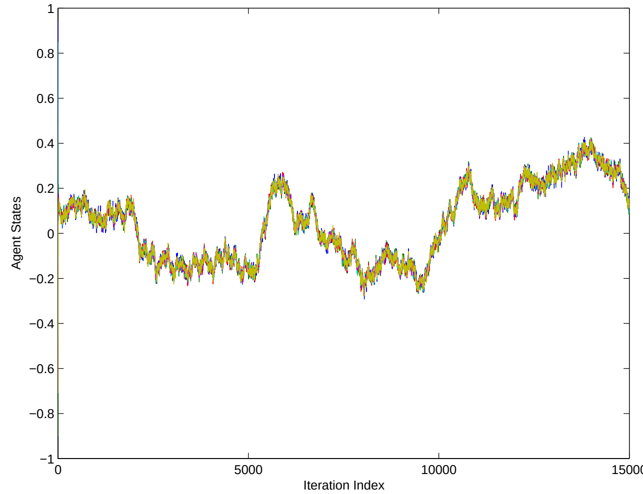


Fig. 4. Asynchronous consensus value driven by bounded noise.

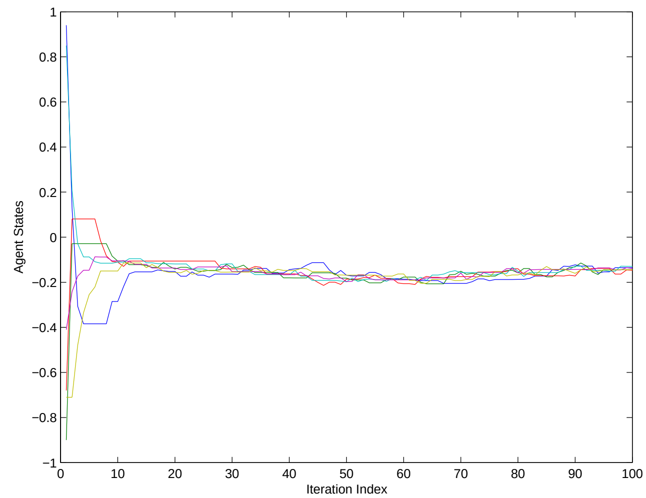


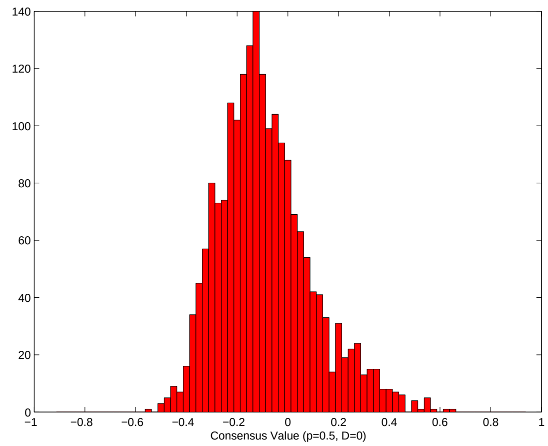
Fig. 5. Asynchronous consensus process can be safely terminated after certain time has passed.

the asynchronous consensus value is (computationally) path-dependent. Fig. 4 shows one realization of the asynchronous consensus process for 15,000 updating events. Although each agent state may become unbounded as $k \longrightarrow \infty$ when driven by the noise input, their inconsistency is bounded. For asynchronous protocols to be useful under noisy communication, a consensus termination condition needs to be identified so that the consensus process can terminated as long as agent state inconsistency is acceptable. Fig. 5 provides a closer look at the consensus process. As we can see, it is safe to terminate the consensus process after certain time has passed.

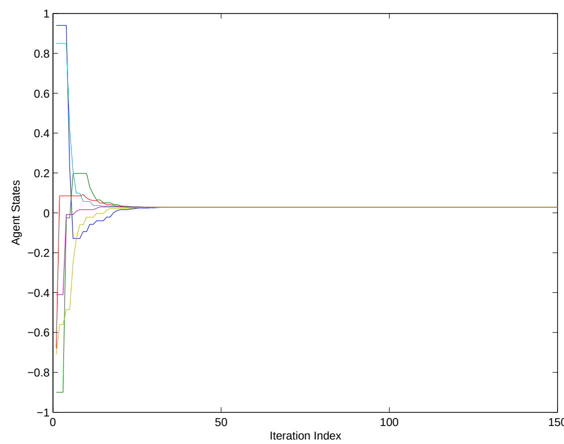
Q2: When does the consensus process need to be terminated under noisy communication? Will an adaptive updating step-size help the convergence of asynchronous consensus protocols?

D. Assumptions on Communication

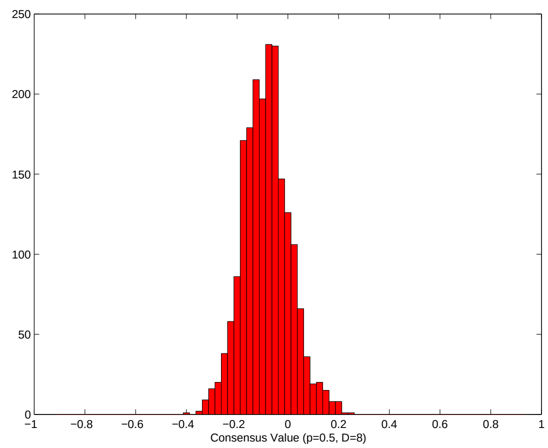
There are numerous consensus results in the literature. It is of great importance to classify them so to help decide



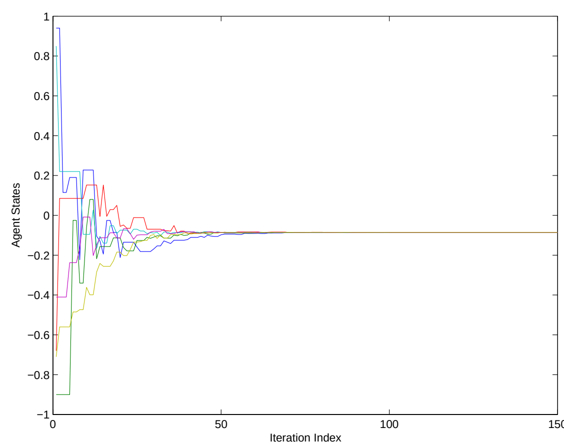
(a) Histogram of consensus value under zero asynchronism



(b) State trajectory under zero asynchronism



(c) Histogram of consensus value with a large delay bound



(d) State trajectory with a large delay bound

Fig. 3. The effects of delay and updating sets in asynchronous consensus process.

about the future research directions. In [6], the existing consensus results are divided into several categories according to the main mathematical tools used in those papers. In the following, we re-examine several important results and focus on three classes of communication assumptions being made, i.e.,

- Direction: Bidirectional vs. Unidirectional;
- Connectivity: Uniform vs. Non-uniform;
- Synchronism: Synchronous vs. Asynchronous.

By uniform connectivity, we mean that a finite and fixed time bound T is involved in the communication assumption on graph connectivity, c.f. Theorem 3.

Let us review two additional synchronous consensus theorems both using protocols (2) but with different communication assumptions.

Theorem 4 ([20]) *Consider a sequence of directed interaction graphs $(V, G(t))$ with common vertex set V. Assume that*

1) *For all $t_0 \in \mathbb{N}$ each agent is linked to each other agent across $[t_0, \infty)$ (i.e., each agent is the root of a spanning tree of $\bigcup_{t=t_0}^{\infty} G(t)$);*
2) *There is $T \in \mathbb{N}$ such that for all $t \in \mathbb{N}$ and all $v_1, v_2 \in V$ we have that if $(v_1, v_2) \in G(t)$ then v_2 is linked to v_1 across $[t, t+T]$ (i.e., there is a directed path from v_2 to v_1 in $\bigcup_{t=t}^{t+T} G(t)$).*

Then consensus is asymptotically reachable.

Remark 2 *In the degenerate case $T = 0$, 2) is equivalent to the condition that there is a bidirectional link between v_1 and v_2.*

Theorem 5 ([12], [19]) *Assume the interaction graphs are bidirectional for all $t \in \mathbb{N}$. If for all $t_0 \in \mathbb{N}$ the sequence of graphs $(V, G(t))$ has a spanning tree in $\bigcup_{t=t_0}^{\infty} G(t)$), then consensus is asymptotically reachable.*

We now categorize in Table I all the aforementioned theorems according to their communication assumptions. This way of categorizing consensus results is motivated by a private communication with L. Moreau. Since the spanning tree requirement plays a role in all the theorems, we do not explicitly consider this assumption in the table.

We show the relationship between the theorems in the following diagram, where the arrows show that one theorem

TABLE I

A CATEGORIZATION OF EXISTING CONSENSUS RESULTS

Theorems	Direction	Connectivity	Synchronism
1	Unidirect.	Fixed	Sync.
2	Unidirect.	Fixed	Async.
3	Unidirect.	Uniform	Sync.
4	Unidirect.	Non-uniform + 2)	Sync.
5	Bidirect.	Non-uniform	Sync.

implies the other.

$$\begin{array}{ccccccc} \text{Th. } 2 & \Rightarrow & \text{Th. } 3 & \not\Leftrightarrow & \text{Th. } 4 & \Rightarrow & \text{Th. } 5 \\ \Downarrow & & & & & & \\ \text{Th. } 1 & & & & & & \end{array}$$

There are a number of open questions that concern convergence under different assumptions, e.g.,

Q3: What is the least set of assumptions needed to guarantee that the synchronous/asynchronous consensus is reachable?

Some of the questions will be discussed in the full version of the paper.

IV. A MULTI-VEHICLE SIMULATOR

In order to implement and evaluate consensus protocols, a simulation environment is needed. We developed a Java-based multi-vehicle simulator (MultiVeh) on top of JProwler; JProwler is a discrete event simulator for prototyping, verifying and analyzing communication protocols of ad-hoc wireless networks. TJProwler was selected because it has been widely used in the simulation study of wireless sensor and actuator applications. Each vehicle is modeled as a point mass with fully actuated dynamics and has the ability to move in two dimensions with constant speed but varying headings (orientations). In particular the consensus parameter is the heading of the moving vehicles. In addition, each vehicle is able to communicate with others using wireless (Gaussian or Rayleigh) channels with the MAC protocol for MICA2 sensor nodes (a variant of CSMA). The collision avoidance mechanism is not considered at this time. The vehicle mobility creates a dynamic interaction graph and the MAC protocol imposes an asynchronous and uncertain message exchange among vehicles. A screen shot of the simulator is provided in Fig. 6, where triangles denote simulated vehicles and lines represent the communication link between them.

In the following, we concentrate on the inherent asynchronism in the system operation, which also justifies the usefulness of an asynchronous framework in studying consensus problems. Individual vehicle behavior could be described as a sequence of periodically (or quasi periodically) occurring events. Two events actually govern the vehicles' behavior, the *moving* event and the *updating* event. The moving event is translated into the movement of the vehicle to a new position according to its velocity and heading. The updating event includes two steps that a vehicle has to complete. First, a vehicle computes its new heading using the heading information gathered from its neighbors. This information

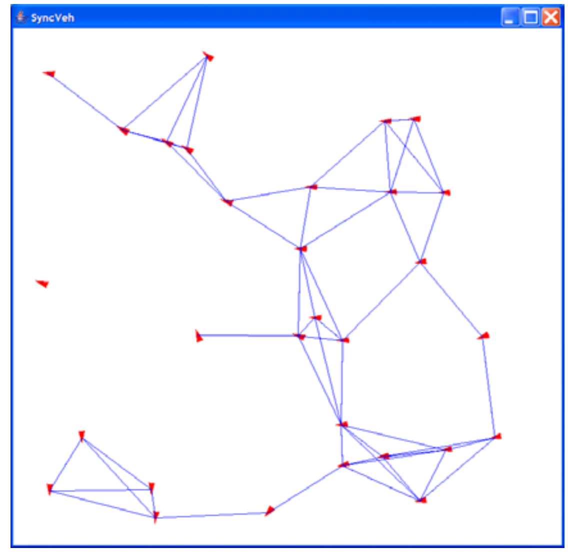


Fig. 6. A multi-vehicle simulator.

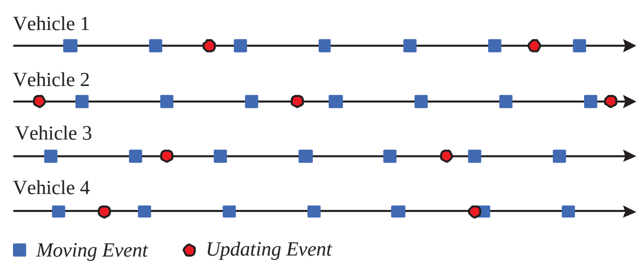


Fig. 7. Vehicles operate under an asynchronous mode.

is collected by the vehicle since the last updating event. The second step is to broadcast its new heading to all of its neighbors, where neighbors are considered as those vehicles that can receive the message.

Assume that all the vehicles are initially synchronized and use the same channel to transmit their heading information. However, all the vehicles would fail to receive the messages due to packet collisions. It is known that the performance of the wireless protocols (CSMA/ALOHA) improves when vehicles are trying to access the medium at different time instants, with sufficient time interval between two successive tries. Successful transmission heavily depends on the number of vehicles and the rate at which new messages are generated. Fig. 7 illustrates the possible timing relationship between different events and different vehicles. A simulation example in Fig. 8 clearly shows the asynchronous updating of the heading of a group of vehicles. Another drawback of the wireless ad-hoc communication is the lack of guarantee of delivery. The time that a vehicle might need to wait to successfully transmit a message is unbounded. Such long delays of a vehicle to inform its neighbor could result in disconnected graph components. To avoid packet collisions and long time delays, the vehicles should spread medium access over the available time slots. If the available time slots are not enough then the rate of updating messages

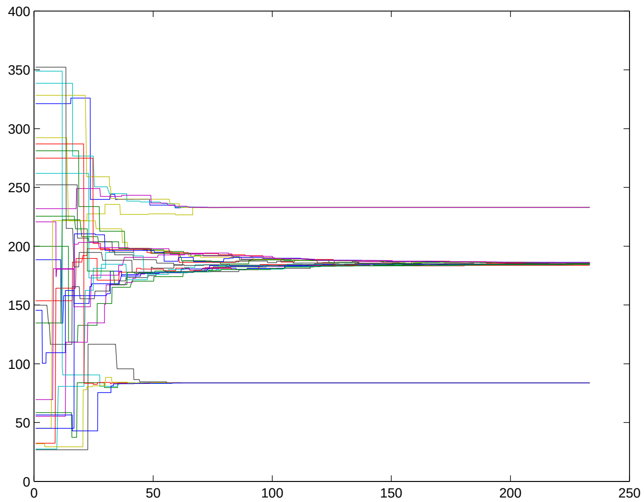


Fig. 8. Asynchronous updating of vehicles' heading information.

should be reduced. But, limited communication in the group is equivalent to "small neighborhoods," leading to weakly connected interaction graph and in turn affect vehicles' dynamics. Two subgroups of vehicles may move toward different directions and it is impossible for them to reach consensus in the future due to the communication range limitation as demonstrated in Fig. 8. It will be interesting to develop a scheme to prevent this from happening. In summary, the information flow among multiple vehicles and vehicles' dynamics play an important role in the coordinated behavior of these vehicles.

V. Discussions and Conclusions

By introducing asynchronism, we add a new dimension to consensus problems. Nevertheless, the analysis of asynchronous algorithms is more difficult than that of their synchronous counterparts. In this paper, a number of recent results were summarized. Open problems still exist and the research is ongoing. Simulations are instrumental in studying asynchronous consensus problems under time-varying topology.

References

[1] D. Bauso, L. Giarre, and R. Pesenti, "Attitude alignment of a team of UAVs under decentralized information structure," *Proc. 2003 IEEE Conf. Contr. Applicat.*, 2003, pp. 486-491.

[2] R. W. Beard and V. Stepanyan, "Information consensus in distributed multiple vehicle coordinated control," *Proc. 42nd IEEE CDC*, Maui, HI, 2003, pp. 2029-2034.

[3] G. Beni and P. Liang, "Pattern reconfiguration in swarms - convergence of a distributed asynchronous and bounded iterative algorithm," *IEEE Trans. R&A*, vol. 12, no. 3, pp. 485-490, 1996.

[4] D. P. Bertsekas and J. N. Tsitsiklis, *Parallel and Distributed Computation: Numerical Methods*, Prentice-Hall, Englewood Cliffs, NJ 1989.

[5] G. A. de Castro and F. Paganini, "Convex synthesis of controllers for consensus," *Proc. 2004 ACC*, Boston, MA, 2004, pp. 4933-4938.

[6] L. Fang and P. J. Antsaklis, "Information consensus of asynchronous discrete-time multi-agent systems," *American Contr. Conf.*, 2005.

[7] A. Frommer and D. B. Szyld, "On asynchronous iterations," *J. Computational and Applied Math.*, vol. 123, pp. 201-216, 2000.

[8] Y. Hatano and M. Mesbahi, "Agreement over random networks," *Proc. 43rd IEEE CDC*, Atlantis, Bahamas, 2004.

[9] A. Jadbabaie, J. Lin, and A. S. Morse, "Coordination of groups of mobile autonomous agents using nearest neighbor rules," *IEEE Trans. Automat. Contr.*, vol 48, no. 6, pp. 988-1001, 2003.

[10] JProwler, Available at `http://www.isis.vanderbilt.edu/projects/nest/jprowler`

[11] V. S. Kozyakin, "Asynchronous systems: a short survey and problems," `http://euclid.ucc.ie/appliedmath/preprints/BCRI_13_03.pdf`

[12] S. Li and H. Wang, "Multi-agent coordination using nearest neighbor rules: Revisiting the Vicsek model," `http://arxiv.org/abs/cs/0407021`

[13] J. Lin, A. S. Morse, and B. D. O. Anderson, "The multi-agent rendezvous problem - The asynchronous case," *Proc. 43rd IEEE CDC*, Atlantis, Bahamas, 2004.

[14] Z. Lin, M. Broucke, and B. Francis, "Local control strategies for groups of mobile autonomous agents," *IEEE Trans. Automat. Contr.*, vol. 49, no. 4, pp. 622-629, 2004.

[15] Y. Liu, K. Passino, and M. Polycarpou, "Stability analysis of one-dimensional asynchronous swarms," *Proc. 2001 ACC*, Arlington, VA, 2001, pp. 716-721.

[16] ——, "Stability analysis of one-dimensional asynchronous mobile swarms," *Proc. 40th IEEE CDC*, Orlando, FL, 2001, pp. 1077-1082.

[17] ——, "Stability analysis of M-dimensional asynchronous swarms with a fixed communication topology," *Proc. 2002 ACC*, Anchorage, AK, 2002, pp. 1278-1283.

[18] M. Mehyar, D. Spanos, J. Pongsajapan, S. Low, and R. Murray, "Distributed averaging on peer-to-peer networks," submitted to *IPSN 2005*.

[19] L. Moreau, "Leaderless coordination via bidirectional and unidirectional time-dependent communication," *Proc. 42nd IEEE CDC*, Maui, HI, 2003, pp. 3070-3075.

[20] L. Moreau, "A note on leadless coordination via bidirectional and unidirectional time-dependent communication," *MTNS'04*, Belgium, 2004.

[21] L. Moreau, "Stability of multi-agent systems with time-dependent communication links," *IEEE Trans. Automat. Contr.* vol. 50, no. 2, pp. 169-182, 2005.

[22] R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays," *IEEE Trans. Automat. Contr.*, vol. 49, no. 9, pp. 1520-1533, 2004.

[23] W. Ren and R. W. Beard, "Consensus of information under dynamically changing interaction topologies," *Proc. 2004 ACC*, Boston, MA, 2004, pp. 4939-4944.

[24] W. Ren and R. W. Beard, "Dynamic consensus seeking in distributed multi-agent coordinated control," submitted to *IEEE 2004 Int. Conf. R&A*, 2004.

[25] W. Ren, R. W. Beard, and T. W. McLain,"Coordination variables and consensus building in multiple vehicle systems," *Lecture Notes in Control and Information Systems*, vol. 309, Springer-Verlag, pp. 171-188, 2004.

[26] W. Ren, R. W. Beard, and E. M. Atkins, "A survey of consensus problems in multi-agent coordination," *American Control Conf.*, 2005.

[27] A. V. Savkin, "Coordinated collective motion of groups of autonomous mobile robots: Analysis of Vicsek's model," *IEEE Trans. Automat. Contr.*, vol. 49, no. 6, pp. 981-983, 2004.

[28] J. J. E. Slotine and W. Wang, "A study of synchronization and group cooperation using partial contraction theory," *Block Island Workshop on Cooperat. Contr.*, V.J. Kumar, N.E. Leonard, A.S. Morse Eds., Springer-Verlag, 2003.

[29] Y. Su, A. Bhaya, E. Kaszkurewicz, and V. S. Kozyakin, "Further results on convergence of asynchronous linear iterations," *Linear Algebra and Applicat.*, vol. 281, pp. 11-24, 1998.

[30] F. J. Vazquez-Abad, C. G. Cassandras, and V. Julka, "Centralized and decentralized asynchronous optimization of stochastic discrete-event systems," *IEEE Trans. AC*, vol. 43, no. 5, pp. 631-655, 1998.

[31] L. Xiao and S. Boyd, "Fast linear iterations for distributed averaging," *Proc. 42nd IEEE CDC*, Maui, HI, 2003, pp. 4997-5002.