On synchronous robotic networks – Part I: Models, tasks and complexity

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Abstract

This paper proposes a formal model for a network of robotic agents that move and communicate. Building on concepts from distributed computation, robotics and control theory, we define notions of robotic network, control and communication law, coordination task, and time and communication complexity. We illustrate our model and compute the proposed complexity measures in the example of a network of locally connected agents on a circle that agree upon a direction of motion and pursue their immediate neighbors.

I. Introduction

Problem motivation: The study of networked mobile systems presents new challenges that lie at the confluence of communication, computing, and control. In this paper we consider the problem of designing joint communication protocols and control algorithms for groups of agents with controlled mobility. For such groups of agents we define the notion of communication and control law by extending the classic notion of distributed algorithm in synchronous networks. Decentralized control strategies are appealing for networks of robots because they can be scalable and they provide robustness to vehicle and communication failures.

One of our key objectives is to develop a theory of time and communication complexity for motion coordination algorithms. Hopefully, our formal model will be suitable to analyze objectively the performance of various coordination algorithms. It is our contention that such a theory is required to assess the complex trade-offs between

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computation, communication and motion control or, in other words, to establish what algorithms are *scalable* and practically implementable in large networks of mobile autonomous agents. The need for modern models of computation in wireless and sensor network applications is discussed in the well-known report [1], [2].

Literature review: To study complexity of motion coordination, our starting points are the standard notions of *synchronous and asynchronous networks* in distributed and parallel computation, e.g., see [3] and, with an emphasis on numerical methods, [4]. This established body of knowledge, however, is not applicable to the robotic network setting because of the agents' mobility and the ensuing dynamic communication topology.

An important contribution towards a network model of mobile interacting robots is introduced in [5], see also [6]. This model consists of a group of identical "distributed anonymous mobile robots" characterized as follows: no explicit communication takes place between them, and at each time instant of an "activation schedule," each robot senses the relative position of all other robots and moves according to a pre-specified algorithm. A related model is presented in [7], where as few capabilities as possible are assumed on the agents, with the objective of understanding the limitations of multi-agent networks. A brief survey of models, algorithms, and the need for appropriate complexity notions is presented in [8]. Recently, a notion of communication complexity for control and communication algorithms in multi-robot systems is analyzed in [9], see also [10]. A general modeling paradigm is discussed in [11], which however does not take into account the specific features of robotic networks. The time complexity of a class of coordinated motion planning problems is computed in [12]. The convergence rate and communication overhead of two cyclic pursuit algorithms is examined in [13].

Statement of contributions: A key contribution of this paper is a model for robotic networks, which properly takes into account some important dynamical, communication and computational aspects of these systems. Our model is meaningful and tractable, it describes feasible operations and their costs, and it allows us to study tradeoffs between control and communication problems. We summarize our approach as follows. A *robotic network* is a group of robotic agents moving in space and endowed with communication capabilities. The agents' positions obey a differential equation and the communication topology is a function of the agents' relative positions. Each agent repeatedly performs communication, computation and physical motion as described next. At predetermined time instants, the agents exchange information along the communication graph and update their internal state. Between successive communication instants, the agents move according to a motion control law, computed as a function of the agent location and of the available information gathered through communication with other agents. In short, a *control and communication law* for a robotic network consists of a message-generation function (what do the agents communicate?), a state-transition function (how do the agents update their internal state with the received information?), and a motion control law (how do the agents move between communication rounds?). The *time complexity* of a control and communication law (aimed at solving a given coordination task) is the minimum number of communication rounds required by the agents to achieve the task. We also provide similar definitions for mean and total communication complexity. We show that our notions of complexity satisfy a basic well-posedness property that we refer to as "invariance under reschedulings." To the best of our knowledge, the proposal of studying the complexity of coordination algorithms for synchronous robotic networks under a comprehensive modeling framework presented here is a novel contribution on its own. For a network of locally connected agents evolving on the circle, we define a novel agree-and-pursue control and communication law. This example has the advantages of being both simple to state and illustrative of all aspects of the proposed framework. We prove that the agree-and-pursue law achieves consensus on the agents' direction of motion and equidistance between the agents' positions. Furthermore, we provide upper and lower bounds on the time and total communication complexity to achieve these tasks with the proposed law, and draw some connections with leader election algorithms, see [3]. The complexity estimates build on novel results on the convergence rates of discrete-time dynamical systems defined by tridiagonal Toeplitz and circulant matrices presented in the appendix. The companion paper [14] builds on this framework to establish complexity estimates for motion coordination algorithms that achieve rendezvous and deployment.

Organization: Section II presents a general approach to the modeling of robotic networks by formally introducing notions such as communication graph, control and communication law, and network evolution. Section III defines the notions of task, and of time and communication complexity. We also study the invariance properties of the complexity notions under rescheduling. Section IV provides bounds on the time and communication complexity of the agree-and-pursue law. We gather our conclusions in Section V. The appendix contains the results on discrete-time dynamical systems defined by tridiagonal Toeplitz and circulant matrices.

Notation: We let $\texttt{BooleSet}$ be the set $\{\texttt{true}, \texttt{false}\}$. We let $\prod_{i\in\{1,\dots,N\}} S_i$ denote the Cartesian product of sets $S_1, \dots, S_N$. We let $\mathbb{R}_{>0}$ and $\mathbb{R}_{\geq 0}$ denote the set of strictly positive and non-negative real numbers, respectively. The set of positive natural numbers is denoted by $\mathbb{N}$ and $\mathbb{N}_0$ denotes the set of non-negative integers. For $x \in \mathbb{R}^d$, we denote by $\|x\|_2$ and $\|x\|_\infty$ the Euclidean and the ∞-norm of x, respectively (recall $\|x\|_\infty \leq \|x\|_2 \leq \sqrt{d}\|x\|_\infty$ for $x \in \mathbb{R}^d$). We define the vectors $\mathbf{0} = (0, \dots, 0)$ and $\mathbf{1} = (1, \dots, 1)$ in $\mathbb{R}^d$. For $f, g \colon \mathbb{N} \to \mathbb{R}$, we say that $f \in O(g)$ (respectively, $f \in \Omega(g)$) if there exist $N_0 \in \mathbb{N}$ and $k \in \mathbb{R}_{>0}$ such that $|f(N)| \leq k|g(N)|$ for all $N \geq N_0$

(respectively, $|f(N)| \geq k|g(N)|$ for all $N \geq N_0$). If $f \in O(g)$ and $f \in \Omega(g)$, then we use the notation $f \in \Theta(g)$.

II. A FORMAL MODEL FOR SYNCHRONOUS ROBOTIC NETWORKS

Here we introduce a notion of robotic network as a group of robotic agents with the ability to move and communicate according to a specified communication topology. Our model is inspired by the synchronous network model in [3] and has connections with recent hybrid systems models, e.g., see [15] and see the HIO model in [11].

A. The physical components of a robotic network

Here we introduce our basic definition of physical quantities such as the agents and such as the ability of agents to communicate. We begin by providing a basic model for how each robotic agent moves in space. A *control system* is a tuple (X, U, X_0, f), where

(i) X is a differentiable manifold, called the *state space*;

(ii) U is a compact subset of $\mathbb{R}^m$ containing 0, called the *input space*;

(iii) X_0 is a subset of X, called the *set of allowable initial states*;

(iv) $f\colon X \times U \to TX$ is a C^∞-map with $f(x,u) \in T_xX$ for all $(x,u) \in X \times U$.

We refer to $x \in X$ and $u \in U$ as a *state* and an *input* of the control system, respectively. We will often consider control-affine systems, i.e., control systems with $f(x,u) = f_0(x) + \sum_{a=1}^m f_a(x)\, u_a$. In such a case, we represent f as the ordered family of C^∞-vector fields $(f_0, f_1, \dots, f_m)$ on X.

Definition II.1 (Network of robotic agents) *A* network of robotic agents *(or* robotic network*) $\mathcal{S}$ is a tuple $(I, \mathcal{A}, E_{\text{cmm}})$ consisting of*

(i) $I = \{1, \dots, N\}$*; I is called the* set of unique identifiers (UIDs)*;*

(ii) $\mathcal{A} = \{A^{[i]}\}_{i\in I} = \{(X^{[i]}, U^{[i]}, {X_0}^{[i]}, f^{[i]})\}_{i\in I}$ *is a set of control systems; this set is called the* set of physical agents*;*

(iii) E_{cmm} *is a map from $\prod_{i\in I} X^{[i]}$ to the subsets of $I \times I$; this map is called the* communication edge map.

If $A^{[i]} = (X, U, X_0, f)$ for all $i \in I$, then the robotic network is called uniform. •

Remarks II.2 (i) By convention, we let the superscript $[i]$ denote the variables and spaces which correspond to the agent with unique identifier i; for instance, $x^{[i]} \in X^{[i]}$ and $x_0^{[i]} \in X_0^{[i]}$ denote the state and the initial state of agent $A^{[i]}$, respectively. We refer to $x = (x^{[1]}, \dots, x^{[N]}) \in \prod_{i\in I} X^{[i]}$ as a *state* of the network.

(ii) The map E_{cmm} models the topology of the communication service among the agents: at a network state $x = (x^{[1]}, \dots, x^{[N]})$, two agents at locations $x^{[i]}$ and $x^{[j]}$ can communicate if the pair (i, j) is an edge in $E_{\text{cmm}}(x^{[1]}, \dots, x^{[N]})$. Accordingly, we refer to $(I, E_{\text{cmm}}(x^{[1]}, \dots, x^{[N]}))$ as the *communication graph* at x. When and what agents communicate is discussed in Section II-B. Maps from $\prod_{i \in I} X^{[i]}$ to the subsets of $I \times I$ are called *proximity edge maps* and arise in wireless networks and computational geometry, e.g., see [16]. •

To make things concrete, let us present an interesting example of robotic network. Let $\mathbb{S}^1$ be the unit circle, and measure positions on $\mathbb{S}^1$ counterclockwise from the positive horizontal axis. For $x, y \in \mathbb{S}^1$, we let $\text{dist}(x, y) = \min\{\text{dist}_{\mathsf{c}}(x, y), \text{dist}_{\mathsf{cc}}(x, y)\}$. Here, $\text{dist}_{\mathsf{c}}(x, y) = (x - y) \pmod{2\pi}$ is the clockwise distance, that is, the path length from x to y traveling clockwise. Similarly, $\text{dist}_{\mathsf{cc}}(x, y) = (y - x) \pmod{2\pi}$ is the counterclockwise distance. Here $x \pmod{2\pi}$ is the remainder of the division of x by 2π.

Example II.3 (Locally-connected first-order agents on the circle) For $r \in \mathbb{R}_{>0}$, consider the uniform robotic network $\mathcal{S}_{\text{circle}} = (I, \mathcal{A}, E_{r\text{-disk}})$ composed of identical agents of the form $(\mathbb{S}^1, \mathbb{R}, \mathbb{S}^1, (0, \mathbf{e}))$. Here $\mathbf{e}$ is the vector field on $\mathbb{S}^1$ describing unit-speed counterclockwise rotation. We define the r-disk proximity edge map $E_{r\text{-disk}}$ on the circle by setting $(i, j) \in E_{r\text{-disk}}(\theta^{[1]}, \dots, \theta^{[N]})$ if and only if $i \neq j$ and

$$\text{dist}(\theta^{[i]}, \theta^{[j]}) \leq r \,,$$

where $\text{dist}(x, y)$ is the geodesic distance between the two points x, y on the circle. •

B. Control and communication laws for robotic networks

Here we present a discrete-time communication, continuous-time motion model for the evolution of a robotic network. In our model, the robotic agents evolve in the physical domain in continuous-time and have the ability to exchange information (position and/or dynamic variables) that affect their motion at discrete-time instants.

Definition II.4 (Control and communication law) *Let $\mathcal{S}$ be a robotic network. A* (synchronous, dynamic, feedback) control and communication law $\mathcal{CC}$ *for $\mathcal{S}$ consists of the sets:*

(i) $\mathbb{T} = \{t_\ell\}_{\ell \in \mathbb{N}_0} \subset \mathbb{R}_{\geq 0}$*, an increasing sequence of time instants with no accumulation points, called* communication schedule*;*

(ii) $\mathcal{L}$*, a set containing the* `null` *element, called the* communication alphabet*; elements of $\mathcal{L}$ are called* messages*;*

(iii) $W^{[i]}$, $i \in I$*, sets of values of some* logic variables $w^{[i]}$, $i \in I$*;*

(iv) $W_0^{[i]} \subseteq W^{[i]}$, $i \in I$, *subsets of* allowable initial values *for the logic variables;*

and of the maps:

(i) $\mathrm{msg}^{[i]} \colon \mathbb{T} \times X^{[i]} \times W^{[i]} \times I \to \mathcal{L}$, $i \in I$, *called* message-generation functions*;*

(ii) $\mathrm{stf}^{[i]} \colon \mathbb{T} \times W^{[i]} \times \mathcal{L}^N \to W^{[i]}$, $i \in I$, *called* state-transition functions*;*

(iii) $\mathrm{ctl}^{[i]} \colon \mathbb{R}_{\geq 0} \times X^{[i]} \times X^{[i]} \times W^{[i]} \times \mathcal{L}^N \to U^{[i]}$, $i \in I$, *called* control functions.

If $\mathcal{S}$ *is uniform and if* $W^{[i]} = W$, $\mathrm{msg}^{[i]} = \mathrm{msg}$, $\mathrm{stf}^{[i]} = \mathrm{stf}$, $\mathrm{ctl}^{[i]} = \mathrm{ctl}$, *for all* $i \in I$, *then* $\mathcal{CC}$ *is said to be* uniform *and is described by a tuple* $(W, \{W_0^{[i]}\}_{i \in I}, \mathrm{msg}, \mathrm{stf}, \mathrm{ctl})$. •

We will sometimes refer to a control and communication law as a *motion coordination algorithm*. Roughly speaking, the rationale behind Definition II.4 is the following: for all $i \in I$, to the ith physical agent corresponds a logic process, labeled i, that performs the following actions. First, at each time instant $t_\ell \in \mathbb{T}$, the ith logic process sends to each of its neighbors in the communication graph a message (possibly the `null` message) computed by applying the message-generation function to the current values of $x^{[i]}$ and $w^{[i]}$. After a negligible period of time (therefore, still at time instant $t_\ell \in \mathbb{T}$), the ith logic process updates the value of its logic variables $w^{[i]}$ by applying the state-transition function to the current value of $w^{[i]}$, and to the messages received at t_ℓ. Between communication instants, i.e., for $t \in [t_\ell, t_{\ell+1})$, the motion of the ith agent is determined by applying the control function to the current value of $x^{[i]}$, the value of $x^{[i]}$ at t_ℓ, and the current value of $w^{[i]}$. This idea is formalized as follows.

Definition II.5 (Evolution of a robotic network) *Let* $\mathcal{S}$ *be a robotic network and* $\mathcal{CC}$ *be a control and communication law for* $\mathcal{S}$. *The* evolution *of* $(\mathcal{S}, \mathcal{CC})$ *from initial conditions* $x_0^{[i]} \in X_0{}^{[i]}$ *and* $w_0^{[i]} \in W_0^{[i]}$, $i \in I$, *is the collection of curves* $x^{[i]} \colon [t_0, \infty) \to X^{[i]}$ *and* $w^{[i]} \colon \mathbb{T} \to W^{[i]}$, $i \in I$, *satisfying*

$$\dot{x}^{[i]}(t) = f\Big(x^{[i]}(t),\, \mathrm{ctl}^{[i]}\big(t, x^{[i]}(t), x^{[i]}(\lfloor t \rfloor_{\mathbb{T}}), w^{[i]}(\lfloor t \rfloor_{\mathbb{T}}), y^{[i]}(\lfloor t \rfloor_{\mathbb{T}})\big)\Big),$$

where $\lfloor t \rfloor_{\mathbb{T}} = \max\{t_\ell \in \mathbb{T} \mid t_\ell < t\}$, *and*

$$w^{[i]}(t_\ell) = \mathrm{stf}^{[i]}(t_\ell, w^{[i]}(t_{\ell-1}), y^{[i]}(t_\ell))\,,$$

with $x^{[i]}(t_0) = x_0^{[i]}$, *and* $w^{[i]}(t_{-1}) = w_0^{[i]}$, $i \in I$. *In the previous equations,* $y^{[i]} \colon \mathbb{T} \to \mathcal{L}^N$ *(describing the messages received by agent* i*) has components* $y_j^{[i]}(t_\ell)$, *for* $j \in I$, *given by*

$$y_j^{[i]}(t_\ell) = \begin{cases} \mathrm{msg}^{[j]}(t_\ell, x^{[j]}(t_\ell), w^{[j]}(t_{\ell-1}), i), & \textit{if } (i,j) \in E_{\mathrm{cmm}}\big(x^{[1]}(t_\ell), \dots, x^{[N]}(t_\ell)\big), \\ \texttt{null}, & \textit{otherwise}. \end{cases}$$ •

With slight abuse of notation, we let $t \mapsto (x(t), w(t))$ denote the curves $x^{[i]}$ and $w^{[i]}$, for $i \in \{1, \dots, N\}$.

Remark II.6 (Properties of control and communication laws) A control and communication law $\mathcal{CC}$ is:

(i) *time-independent* if all message-generation, state-transition and control functions are time-independent; in this case $\mathcal{CC}$ can be described by maps of the form $\mathrm{msg}^{[i]} \colon X^{[i]} \times W^{[i]} \times I \to \mathcal{L}$, $\mathrm{stf}^{[i]} \colon W^{[i]} \times \mathcal{L}^N \to W^{[i]}$, and $\mathrm{ctl}^{[i]} \colon X^{[i]} \times X^{[i]} \times W^{[i]} \times \mathcal{L}^N \to U^{[i]}$, for $i \in I$;

(ii) *static* if $W^{[i]}$ is a singleton for all $i \in I$; in this case $\mathcal{CC}$ can be described by a tuple $(\mathbb{T}, \mathcal{L}, \{\mathrm{msg}^{[i]}\}_{i \in I}, \{\mathrm{ctl}^{[i]}\}_{i \in I}$, with $\mathrm{msg}^{[i]} \colon \mathbb{T} \times X^{[i]} \times I \to \mathcal{L}$, and $\mathrm{ctl}^{[i]} \colon \mathbb{R}_{\geq 0} \times X^{[i]} \times X^{[i]} \times \mathcal{L}^N \to U^{[i]}$, for $i \in I$;

(iii) *data-sampled* if the control functions $\mathrm{ctl}^{[i]}$, $i \in I$, have the following property: given a time t, a logic state $w^{[i]} \in W^{[i]}$, an array of messages $y^{[i]} \in \mathcal{L}^N$, a current state $x^{[i]}$, and a state at last sample time $x^{[i]}_{\text{smpld}}$, the control input $\mathrm{ctl}(t, x^{[i]}, x^{[i]}_{\text{smpld}}, w^{[i]}, y^{[i]})$ is independent of $x^{[i]}$. In this case the control functions in $\mathcal{CC}$ can be described by maps of the form $\mathrm{ctl}^{[i]} \colon \mathbb{R}_{\geq 0} \times X^{[i]} \times W^{[i]} \times \mathcal{L}^N \to U^{[i]}$, for $i \in I$. •

Remark II.7 (Idealized aspects of communication model) Let us discuss two limitations regarding the proposed communication model. We refer to $\mathcal{CC}$ as a *synchronous* control and communication law because the communications between all agents takes always place at the same time for all agents. We do not discuss here the important setting of asynchronous laws (see however the discussion in Section V).

The set $\mathcal{L}$ is used to exchange information between two robotic agents; the message `null` indicates no communication. We assume that the messages in the communication alphabet $\mathcal{L}$ allow us to encode logical expressions such as `true` and `false`, integers, and real numbers. A realistic assumption on $\mathcal{L}$ would be to adopt a finite-precision representation for integers and real numbers in the messages, e.g., $\mathcal{L} = \{\texttt{null}, 0, \dots, 2^{b-1}\}$ would allow messages that can be encoded using up to b bits. Instead, in what follows, we neglect any inaccuracies due to quantization (see however Section V); in other words, we will implicitly assume that b is sufficiently large. In many uniform control and communication laws, the messages interchanged among the network agents are (quantized representations of) the agents' states and logic states. We will identify the corresponding communication alphabet with $\mathcal{L} = (X \times W) \cup \{\texttt{null}\}$; the message generation function $\mathrm{msg}_{\text{std}}(t, x, w, j) = (x, w)$ is referred to as the *standard message-generation function*. •

Remark II.8 (Groups of robotic agents with relative-position sensing) In the model proposed in [5], robots are referred to as "anonymous" and "oblivious" in precisely the same way in which we defined control and communication laws to be uniform and static, respectively. As compared with our notion of robotic network, the model in [5] is more general in that the robots' activations schedules do not necessarily coincide (i.e., this model is asynchronous), and at the same time it is less general in that (1) robots cannot communicate any information other than their respective positions, and (2) each robot observes every other robot's position (i.e., the complete communication graph is adopted; this limitation is not present for example in [6]). Note that a control and communication law, as in our definition, can be implemented on a synchronous model [5] if the law (1) is static and uniform, (2) only relies on communicating the agents' positions (e.g., the message-generation function is the standard one), and (3) entails a control function that only depends on relative positions (as opposed to absolute positions). •

C. The agree-and-pursue control and communication law

Here we present an example of a dynamic control and communication law with the aim of illustrating the proposed framework. The following coordination law is related to leader election algorithms as studied in the distributed algorithms literature, e.g., see [3] (more will be said about this analogy in Remark IV.3), and to cyclic pursuit algorithms as studied in the control literature, e.g., see [17], [13]. Despite the apparent simplicity, this example is remarkable in that it combines a leader election task (in the logic variables) with a uniform agent deployment task (in the state variables), arguably two of the most basic tasks in distributed algorithms and cooperative control, respectively. Another advantage of the agree-and-pursue law is that its correctness, performance and cost can be fully characterized. We will come back to this later in Section IV.

From Example II.3, we consider the uniform network $\mathcal{S}_{\text{circle}}$ of locally-connected first-order agents in $\mathbb{S}^1$. We now define the agree-and-pursue law, denoted by $\mathcal{CC}_{\text{agr-pursuit}}$, as the uniform, time-independent and data-sampled law loosely described as follows:

> *[Informal description]* The logic variables are $\texttt{drctn}$ (the agent's direction of motion) taking values in $\{\texttt{c}, \texttt{cc}\}$ and $\texttt{prior}$ (the agent's priority) taking values in I. At each communication round, each agent transmits its position and its logic variables and sets its logic variables to those of the incoming message with the largest value of $\texttt{prior}$. (Therefore, the logic state with the largest $\texttt{prior}$ will propagate throughout the network.) Between communication rounds, each agent moves in the counterclockwise or clockwise direction depending on whether its logic variable $\texttt{drctn}$ is $\texttt{cc}$ or $\texttt{c}$. For $k_{\text{prop}} \in]0, \frac{1}{2}[$, each agent moves k_{prop} times the distance to the immediately next neighbor in the chosen direction, or, if no

neighbors are detected, k_{prop} times the communication range r.

Next, we define the law formally. Each agent has logic variables $w = (w_1, w_2)$, where $w_1 = \texttt{drctn} \in \{\texttt{cc}, \texttt{c}\}$, with arbitrary initial value, and $w_2 = \texttt{prior} \in I$, with initial value set equal to the agent's identifier i. In other words, we define $W = \{\texttt{cc}, \texttt{c}\} \times I$, and we set $W_0^{[i]} = \{\texttt{cc}, \texttt{c}\} \times \{i\}$. Each agent $i \in I$ operates with the standard message-generation function, i.e., we set $\mathcal{L} = (\mathbb{S}^1 \times W) \cup \{\texttt{null}\}$ and $\text{msg}^{[i]} = \text{msg}_{\text{std}}$, where $\text{msg}_{\text{std}}(\theta, w, j) = (\theta, w)$. Given a logic state $w \in W$ and an array of messages $y \in \mathcal{L}^N$, the state-transition function is defined by

$$\text{stf}(w, y) = \max\{w_{\text{rcvd}} \in W \mid \exists \theta_{\text{rcvd}} \in \mathbb{S}^1 \text{ s.t. } (\theta_{\text{rcvd}}, w_{\text{rcvd}}) = y_j, \text{for some } j \in I\},$$

where we define an ordering in the logic set W by saying that $(\texttt{drctn}_1, \texttt{prior}_1) > (\texttt{drctn}_2, \texttt{prior}_2)$ if $\texttt{prior}_1 > \texttt{prior}_2$. For $k_{\text{prop}} \in \mathbb{R}_{>0}$, given a logic state $w \in W$, an array of messages $y \in \mathcal{L}^N$, and a state at last sample time θ_{smpld}, the control function is

$$\text{ctl}(\theta_{\text{smpld}}, w, y) = k_{\text{prop}} \begin{cases} \min(\{r\} \cup \{\text{dist}_{\texttt{cc}}(\theta_{\text{smpld}}, \theta_{\text{rcvd}}) \mid \text{for all non-null } (\theta_{\text{rcvd}}, w_{\text{rcvd}}) \in y\}), & \text{if } \texttt{drctn} = \texttt{cc}, \\ -\min(\{r\} \cup \{\text{dist}_{\texttt{c}}(\theta_{\text{smpld}}, \theta_{\text{rcvd}}) \mid \text{for all non-null } (\theta_{\text{rcvd}}, w_{\text{rcvd}}) \in y\}), & \text{if } \texttt{drctn} = \texttt{c}. \end{cases}$$

An implementation of this control and communication law is shown in Figure 1. Along the evolution, all agents agree upon a common direction of motion and, after suitable time, they reach a uniform distribution.

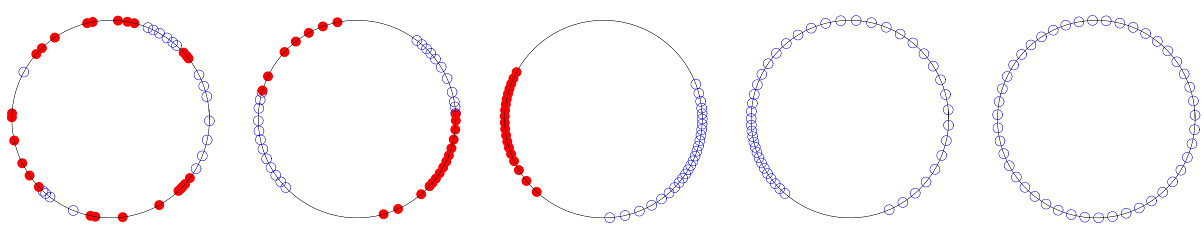

Fig. 1. The agree-and-pursue control and communication law in Section II-C with $N = 45$, $r = 2\pi/40$, and $k_{\text{prop}} = 7/16$. Disks and circles correspond to agents moving counterclockwise and clockwise, respectively. The initial positions and the initial directions of motion are randomly generated. The five pictures depict the network state at times $0, 9, 24, 100, 800$.

III. Coordination tasks and complexity measures

In this section we introduce concepts and tools useful to analyze a communication and control law. We address the following questions: What is a coordination task for a robotic network? When does a control and communication law achieve a task? And with what time and communication complexity?

A. Coordination tasks

Our first analysis step is to characterize the correctness properties of a communication and control law. We do so by defining the notion of task and of task achievement by a robotic network.

Definition III.1 (Coordination task) *Let $\mathcal{S}$ be a robotic network and let $\mathcal{W}$ be a set.*

(i) *A* coordination task *for $\mathcal{S}$ is a map $\mathcal{T}\colon \prod_{i\in I} X^{[i]} \times \mathcal{W}^N \to \texttt{BooleSet}$.*

(ii) *If $\mathcal{W} = \emptyset$, then the coordination task is said to be* static *and is described by a map $\mathcal{T}\colon \prod_{i\in I} X^{[i]} \to \texttt{BooleSet}$.*

Additionally, let $\mathcal{CC}$ a control and communication law for $\mathcal{S}$.

(i) *The law $\mathcal{CC}$ is* compatible *with the task $\mathcal{T}\colon \prod_{i\in I} X^{[i]} \times \mathcal{W}^N \to \texttt{BooleSet}$ if its logic variables take values in $\mathcal{W}$, that is, if $W^{[i]} = \mathcal{W}$, for all $i \in I$.*

(ii) *The law $\mathcal{CC}$* achieves *the task $\mathcal{T}$ if it is compatible with it and if, for all initial conditions $x_0^{[i]} \in X_0^{[i]}$ and $w_0^{[i]} \in W_0^{[i]}$, $i \in I$, the corresponding network evolution $t \mapsto (x(t), w(t))$ has the property that there exists $T \in \mathbb{R}_{>0}$ such that $\mathcal{T}(x(t), w(t)) = \texttt{true}$ for all $t \geq T$.* •

Remark III.2 (Temporal logic) Loosely speaking, achieving a task means obtaining and maintaining a specified pattern in the position of the agents or of their logic variables. In other words, the task is achieved if *at some time* and *for all subsequent times* the predicate evaluates to true along system trajectories. It is possible to consider more general tasks based on more expressive predicates on trajectories. Such predicates can be defined through various forms of temporal and propositional logic, e.g., see [18]. In particular, (linear) temporal logic contains certain constructs that allow reasoning in terms of time and is hence appropriate for robotic applications, as argued for example in [19]. Network tasks such as periodically visiting a desired set of configurations could easily be encoded with such temporal logic statements. •

Example III.3 (Agreement and equidistance tasks) From Example II.3, consider the uniform network $\mathcal{S}_{\text{circle}}$ of locally-connected first-order agents in $\mathbb{S}^1$. From Example II-C, recall the agree-and-pursue control and communication law $\mathcal{CC}_{\text{agr-pursuit}}$ with logic variables taking values in $W = \{\texttt{cc}, \texttt{c}\} \times I$. There are two tasks of interest. First, we define the *agreement task* $\mathcal{T}_{\texttt{drctn}} \colon (\mathbb{S}^1)^N \times W^N \to \texttt{BooleSet}$ by

$$\mathcal{T}_{\texttt{drctn}}(\theta, w) = \begin{cases} \texttt{true}, & \text{if } \texttt{drctn}^{[1]} = \cdots = \texttt{drctn}^{[N]}, \\ \texttt{false}, & \text{otherwise}, \end{cases}$$

where $\theta = (\theta^{[1]}, \dots, \theta^{[N]})$, $w = (w^{[1]}, \dots, w^{[N]})$, and $w^{[i]} = (\texttt{drctn}^{[i]}, \texttt{prior}^{[i]})$, for $i \in I$. Furthermore, for $\varepsilon \in \mathbb{R}_{>0}$, we define the static *equidistance task* $\mathcal{T}_{\text{eqdstnc}} \colon (\mathbb{S}^1)^N \to \texttt{BooleSet}$ by

$$\mathcal{T}_{\varepsilon\text{-eqdstnc}}(\theta) = \begin{cases} \texttt{true}, & \text{if } \left|\min_{j \neq i} \text{dist}_{\texttt{c}}(\theta^{[i]}, \theta^{[j]}) - \min_{j \neq i} \text{dist}_{\texttt{cc}}(\theta^{[i]}, \theta^{[j]})\right| < \varepsilon, \text{ for all } i \in I, \\ \texttt{false}, & \text{otherwise}. \end{cases}$$

In other words, $\mathcal{T}_{\varepsilon\text{-eqdstnc}}$ is true when, for every agent, the clockwise distance to the closest clockwise neighbor and the counterclockwise distance to the closest counterclockwise neighbor are approximately equal. •

B. Complexity notions for control and communication laws and for coordination tasks

We are finally ready to define the key notions of time and communication complexity. These notions describe the cost that a certain control and communication law incurs while completing a certain coordination task. We also define the complexity of a task to be the infimum of the costs incurred by all laws that achieve that task.

First, we define the time complexity of an achievable task as the minimum number of communication rounds needed by the agents to achieve the task $\mathcal{T}$.

Definition III.4 (Time complexity) *Let $\mathcal{S}$ be a robotic network and let $\mathcal{T}$ be a coordination task for $\mathcal{S}$. Let $\mathcal{CC}$ be a control and communication law for $\mathcal{S}$ compatible with $\mathcal{T}$.*

(i) *The* (worst-case) time complexity to achieve $\mathcal{T}$ with $\mathcal{CC}$ from $(x_0, w_0) \in \prod_{i \in I} X_0^{[i]} \times \prod_{i \in I} W_0^{[i]}$ *is*

$$\text{TC}(\mathcal{T}, \mathcal{CC}, x_0, w_0) = \inf \left\{ \ell \mid \mathcal{T}(x(t_k), w(t_k)) = \texttt{true}, \textit{ for all } k \geq \ell \right\},$$

where $t \mapsto (x(t), w(t))$ is the evolution of $(\mathcal{S}, \mathcal{CC})$ from the initial condition (x_0, w_0).

(ii) *The* (worst-case) time complexity to achieve $\mathcal{T}$ with $\mathcal{CC}$ *is*

$$\text{TC}(\mathcal{T}, \mathcal{CC}) = \sup \left\{ \text{TC}(\mathcal{T}, \mathcal{CC}, x_0, w_0) \mid (x_0, w_0) \in \prod_{i \in I} X_0^{[i]} \times \prod_{i \in I} W_0^{[i]} \right\}.$$ •

The time complexity of a task can be also defined by taking the infimum among all compatible laws that achieve it.

Next, we define the notions of mean and total communication complexities for an algorithm. As usual, consider a network $\mathcal{S}$ and a control and communication law $\mathcal{CC}$. With these data we can discuss the cost of realizing one communication round. At time instants in $\mathbb{T}$, each agent generates a certain number of messages in $\mathcal{L}$, destined to neighboring agents as defined by the communication edge map. Indicate the set of all non-null messages generated during one communication round with

$$\mathcal{M}(t,x,w) = \{(i,j) \in E_{\text{cmm}}(x) \mid \text{msg}^{[i]}(t,x^{[i]},w^{[i]},j) \neq \texttt{null}\}.$$

To compute the cost of delivering all such messages to the intended recipient, we introduce the following function.

Definition III.5 (One-round cost) *A function* $\mathrm{C}_{\text{rnd}} \colon 2^{I\times I} \to \mathbb{R}_{\geq 0}$ *is a* one-round cost function *if* $\mathrm{C}_{\text{rnd}}(\emptyset) = 0$*, and* $S_1 \subset S_2 \subset I \times I$ *implies* $\mathrm{C}_{\text{rnd}}(S_1) \leq \mathrm{C}_{\text{rnd}}(S_2)$*. A one-round cost function* C_{rnd} *is* additive *if, for all* $S_1, S_2 \subset I \times I$*,* $S_1 \cap S_2 = \emptyset$ *implies* $\mathrm{C}_{\text{rnd}}(S_1 \cup S_2) = \mathrm{C}_{\text{rnd}}(S_1) + \mathrm{C}_{\text{rnd}}(S_2)$. •

More specific detail about the communication cost depends necessarily on the type of communication service (e.g., unidirectional versus omnidirectional) available between the agents. We postpone our discussion about specific functions C_{rnd} to the next subsection.

Definition III.6 (Communication complexity) *Let* $\mathcal{S}$ *be a robotic network and let* $\mathcal{CC}$ *be a control and communication law that achieves the task* $\mathcal{T}$*, and let* C_{rnd} *be a one-round communication cost function.*

(i) *The* (worst-case) mean communication complexity *and the* (worst-case) total communication complexity *to achieve* $\mathcal{T}$ *with* $\mathcal{CC}$ *from* $(x_0,w_0) \in \prod_{i\in I} X_0^{[i]} \times \prod_{i \in I} W_0^{[i]}$ *are, respectively,*

$$\mathrm{MCC}(\mathcal{T},\mathcal{CC},x_0,w_0) = \frac{1}{\lambda}\sum_{\ell=0}^{\lambda-1} \mathrm{C}_{\text{rnd}} \circ \mathcal{M}(t_\ell, x(t_\ell), w(t_\ell)),$$

$$\mathrm{TCC}(\mathcal{T},\mathcal{CC},x_0,w_0) = \sum_{\ell=0}^{\lambda-1} \mathrm{C}_{\text{rnd}} \circ \mathcal{M}(t_\ell, x(t_\ell), w(t_\ell)),$$

where $\lambda = \mathrm{TC}(\mathcal{CC},\mathcal{T},x_0,w_0)$ *and* $t \mapsto (x(t),w(t))$ *is the evolution of* $(\mathcal{S},\mathcal{CC})$ *from the initial condition* (x_0,w_0)*. (Here* MCC *is defined only for* (x_0,w_0) *with the property that* $\mathcal{T}(x_0,w_0) = \texttt{false}$*.)*

(ii) *The* (worst-case) mean communication complexity *and the* (worst-case) total communication complexity *to achieve* $\mathcal{T}$ *with* $\mathcal{CC}$ *are the supremum of* $\{\mathrm{MCC}(\mathcal{T},\mathcal{CC},x_0,w_0) \mid (x_0,w_0) \in \prod_{i\in I} X_0^{[i]} \times \prod_{i\in I} W_0^{[i]}\}$ *and* $\{\mathrm{TCC}(\mathcal{T},\mathcal{CC},x_0,w_0) \mid (x_0,w_0) \in \prod_{i\in I} X_0^{[i]} \times \prod_{i\in I} W_0^{[i]}\}$*, respectively.* •

Note that by (worst-case) mean communication complexity we mean to consider the worst-case over all initial conditions and mean over the time required to achieve the task.

Remark III.7 (Infinite-horizon mean communication complexity) The mean communication complexity MCC measures the average cost of the communication rounds required to achieve a task over a finite time horizon; a similar statement holds for the total communication complexity TCC. One might be interested in a notion of mean communication complexity required to maintain true the task for all times. Accordingly, the infinite-horizon mean communication complexity of $\mathcal{CC}$ from initial conditions (x_0, w_0) is

$$\text{IH-MCC}(\mathcal{CC}, x_0, w_0) = \lim_{\lambda \to +\infty} \frac{1}{\lambda} \sum_{\ell=0}^{\lambda} \mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_\ell, x(t_\ell), w(t_\ell)) \,.$$

Note that a similar notion is presented in [9] for a different robotic network model. •

C. Communication costs in unidirectional and omnidirectional wireless channels

Here, we discuss some modeling aspects of the one-round communication cost function described in Definition III.5. Broadly speaking, it is very difficult to encompass with a single abstract model the cost of all possible communication technologies. In *unidirectional* models of communication (e.g., wireless networks with unidirectional antennas, communication based on TCP-IP protocols) messages are sent in a point-to-point-wise fashion. Instead, in *omnidirectional* models of communication (e.g., wireless networks equipped with omnidirectional antennas), a single transmission made by a node can be heard by several other nodes simultaneously. Motivated by these considerations, the rest of this paper relies on the following simplified models:

(i) For a unidirectional communication model, $\mathrm{C}_{\mathrm{rnd}}(\mathcal{M})$ is proportional to the number messages in $\mathcal{M}$, that is, $\mathrm{C}_{\mathrm{rnd}}(\mathcal{M}) = c_0 \cdot \mathrm{cardinality}(\mathcal{M})$, where $c_0 \in \mathbb{R}_{>0}$ is the cost of sending a single message. This one-round cost function is additive. This number is trivially bounded by twice the number of edges of the complete graph, which is $N(N-1)$. Therefore, for unidirectional models of communication, we have $\mathrm{MCC}_{\mathrm{unidir}}(\mathcal{T}) \in O(N^2)$.

(ii) For an omnidirectional communication model, $\mathrm{C}_{\mathrm{rnd}}(\mathcal{M})$ is proportional to the number of turns employed to complete a communication round without interference between the agents (this choice is justified in Remark III.8 below). This number is trivially upper bounded by N. Therefore, for omnidirectional models of communication, we have $\mathrm{MCC}_{\mathrm{omnidir}}(\mathcal{T}) \in O(N)$.

Remark III.8 (Omnidirectional wireless communication) Networking protocols for omnidirectional wireless networks rely on a many nested layers to handle, for example, media access, power control, congestion control, and routing, see for instance [2] and references therein.. These layers and the non-trivial interactions among them make it difficult to assess communication costs of individual messages. For example, the Medium Access Control problem consists of determining a minimum number of broadcasting turns required for all agents to communicate their messages without interference. A schematic approach to these problems geared towards our model is as follows: first, from the communication graph (I, E), one constructs the *neighbor-induced* graph $(I, E_{\mathcal{N}})$ by

$$(i, j) \in E_{\mathcal{N}} \quad \text{if and only if} \quad (i, j) \in E \text{ or } (i, k), (j, k) \in E\,, \text{ for some } k \in I.$$

In the new graph $(I, E_{\mathcal{N}})$, the set of neighbors of the agent i is composed by its neighbors in the graph (I, E), together with their respective neighbors. As a second step, one has to compute the *chromatic number* of the graph, i.e., the minimum number of colors $\chi(E_{\mathcal{N}})$ needed to color the agents in such a way that there are no two neighboring agents with the same color (Theorem 5.2.4 in [20] asserts that if a connected graph is neither complete, nor an odd cycle, then $\chi(E_{\mathcal{N}})$ is less than or equal to the maximum valency of the graph). Once the chromatic number has been determined, broadcasting turns can be established according to an ordered sequence of the agents' colors. This approach provides a basic justification for our choice of $\mathrm{C}_{\mathrm{rnd}}$ for omnidirectional communication models. •

D. Rescheduling of control and communication laws for driftless agents

In this section, we discuss the invariance properties of the notions of time and communication complexity under the *rescheduling* of a control and communication law. The idea behind rescheduling is to "spread" the execution of the law over time without affecting the trajectories described by the robotic agents. Our objective is to formalize this idea and to examine the effect on the notions of complexity introduced earlier. For simplicity we consider the setting of static laws; similar results can be obtained for the general setting.

Let $\mathcal{S} = (I, \mathcal{A}, E_{\mathrm{cmm}})$ be a robotic network where each physical agent is a driftless control system. Let $\mathcal{CC} = (\mathbb{N}_0, \mathcal{L}, \{\mathrm{msg}^{[i]}\}_{i\in I}, \{\mathrm{ctl}^{[i]}\}_{i\in I})$ be a static control and communication law. Next, we define a new control and communication law by modifying $\mathcal{CC}$; to do so we introduce some notation. Let $s \in \mathbb{N}$, with $s \leq N$, and let $\mathcal{P}_I = \{I_0, \dots, I_{s-1}\}$ be an *s-partition* of I, that is, $I_0, \dots, I_{s-1} \subset I$ are disjoint and nonempty and $I = \cup_{k=0}^{s-1} I_k$. For $i \in I$, define the message-generation functions $\mathrm{msg}^{[i]}_{\mathcal{P}_I} : \mathbb{N}_0 \times X^{[i]} \times I \to \mathcal{L}$ by

$$\mathrm{msg}^{[i]}_{\mathcal{P}_I}(t_\ell, x, j) = \mathrm{msg}^{[i]}(t_{\lfloor \ell/s \rfloor}, x, j), \tag{1}$$

if $i \in I_k$ and $k = \ell (\operatorname{mod} s)$, and $\mathrm{msg}^{[i]}_{\mathcal{P}_I}(t_\ell, x, j) = \mathtt{null}$ otherwise. According to this message-generation function, only the agents with unique identifier in I_k will send messages at time t_ℓ, with $\ell \in \{k + as\}_{a\in\mathbb{N}_0}$. Equivalently, this can be stated as follows: according to (1), the messages originally sent at the time instant t_ℓ are now rescheduled to be sent at the time instants $t_{F(\ell)-s+1}, \dots, t_{F(\ell)}$, where $F\colon \mathbb{N}_0 \to \mathbb{N}_0$ is defined by $F(\ell) = s(\ell+1)-1$. Figure 2 illustrates this idea.

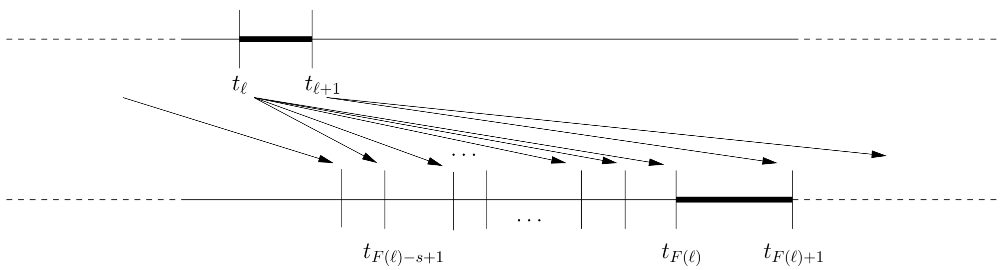

Fig. 2. Under the rescheduling, the messages that are sent at the time instant t_ℓ under the control and communication law $\mathcal{CC}$ are rescheduled to be sent over the time instants $t_{F(\ell)-s+1}, \dots, t_{F(\ell)}$ under the control and communication law $\mathcal{CC}_{(s,\mathcal{P}_I)}$.

For $i \in I$, define the control functions $\mathrm{ctl}^{[i]}\colon \mathbb{R}_{\geq 0} \times X^{[i]} \times X^{[i]} \times \mathcal{L}^N \to U^{[i]}$ by

$$\mathrm{ctl}^{[i]}_{\mathcal{P}_I}(t, x, x_{\mathrm{smpld}}, y) = \frac{t_{F^{-1}(\ell)+1} - t_{F^{-1}(\ell)}}{t_{\ell+1} - t_\ell} \, \mathrm{ctl}^{[i]}\left(h_\ell(t), x, x_{\mathrm{smpld}}, y\right), \tag{2}$$

if $t \in [t_\ell, t_{\ell+1}]$ and $\ell = -1 (\mathrm{mod}\, s)$ and $\mathrm{ctl}^{[i]}_{\mathcal{P}_I}(t, x, x_{\mathrm{smpld}}, y) = 0$ otherwise. Here $F^{-1}\colon \mathbb{N}_0 \to \mathbb{N}_0$ is the inverse of F, defined by $F^{-1}(\ell) = \frac{\ell+1}{s} - 1$, and for $\ell = -1 (\mathrm{mod}\, s)$, the function $h_\ell\colon [t_\ell, t_{\ell+1}] \to [t_{F^{-1}(\ell)}, t_{F^{-1}(\ell)+1}]$ is the unique linear map between the two time intervals. Roughly speaking, the control law $\mathrm{ctl}^{[i]}_{\mathcal{P}_I}$ makes the agent i wait for the time intervals $[t_\ell, t_{\ell+1}]$, with $\ell \in \{as-1\}_{a \in \mathbb{N}}$, to execute any motion. Accordingly, the evolution of the robotic network under the original law $\mathcal{CC}$ during the time interval $[t_\ell, t_{\ell+1}]$ now takes place when all the corresponding messages have been transmitted, i.e., along the time interval $[t_{F(\ell)}, t_{F(\ell)+1}]$. The following definition summarizes this construction.

Definition III.9 (Rescheduling of control and communication laws) *Let $\mathcal{S} = (I, \mathcal{A}, E_{\mathrm{cmm}})$ be a robotic network with driftless physical agents, and let $\mathcal{CC} = (\mathbb{N}_0, \mathcal{L}, \{\mathrm{msg}^{[i]}\}_{i \in I}, \{\mathrm{ctl}^{[i]}\}_{i \in I})$ be a static control and communication law. Let $s \in \mathbb{N}$, with $s \leq N$, and let $\mathcal{P}_I$ be an s-partition of I. The control and communication law $\mathcal{CC}_{(s,\mathcal{P}_I)} = (\mathbb{N}_0, \mathcal{L}, \{\mathrm{msg}^{[i]}_{\mathcal{P}_I}\}_{i \in I}, \{\mathrm{ctl}^{[i]}_{\mathcal{P}_I}\}_{i \in I})$ defined by equations* (1) *and* (2) *is called a $\mathcal{P}_I$-*rescheduling of $\mathcal{CC}$. •

The following result shows that the total communication complexity of $\mathcal{CC}$ remains invariant under rescheduling.

Proposition III.10 (Complexity of rescheduled laws) *With the assumptions of Definition III.9, let $\mathcal{T}\colon \prod_{i \in I} X^{[i]} \to$* `BooleSet` *be a coordination task for $\mathcal{S}$. Then, for all $x_0 \in \prod_{i \in I} X_0^{[i]}$,*

$$\mathrm{TC}(\mathcal{T}, \mathcal{CC}_{(s,\mathcal{P}_I)}, x_0) = s \cdot \mathrm{TC}(\mathcal{T}, \mathcal{CC}, x_0) \, .$$

Moreover, if $\mathrm{C}_{\mathrm{rnd}}$ *is additive, then, for all* $x_0 \in \prod_{i\in I} X_0^{[i]}$

$$\mathrm{MCC}(\mathcal{T}, \mathcal{CC}_{(s,\mathcal{P}_I)}, x_0) = \frac{1}{s} \cdot \mathrm{MCC}(\mathcal{T}, \mathcal{CC}, x_0)\,,$$

and, therefore, $\mathrm{TCC}(\mathcal{T}, \mathcal{CC}_{(s,\mathcal{P}_I)}, x_0) = \mathrm{TCC}(\mathcal{T}, \mathcal{CC}, x_0)$*, i.e., the total communication complexity of* $\mathcal{CC}$ *is invariant under rescheduling.* •

Proof: Let $t \mapsto x(t)$ and $t \mapsto \tilde{x}(t)$ denote the network evolutions starting from $x_0 \in \prod_{i\in I} X_0^{[i]}$ under $\mathcal{CC}$ and $\mathcal{CC}_{(s,\mathcal{P}_I)}$, respectively. From the definition of rescheduling, one can verify that, for all $k \in \mathbb{N}_0$,

$$\tilde{x}^{[i]}(t) = \begin{cases} \tilde{x}^{[i]}(t_{F(k-1)+1}), & \text{for } t \in \bigcup_{\ell=F(k-1)+1}^{F(k)-1} [t_\ell, t_{\ell+1}]\,, \\ x^{[i]}(h_{F(k)}(t)), & \text{for } t \in [t_{F(k)}, t_{F(k)+1}]\,. \end{cases} \tag{3}$$

By definition of $\mathrm{TC}(\mathcal{T}, \mathcal{CC}, x_0)$, we have $\mathcal{T}(x(t_k)) = \texttt{true}$, for all $k \geq \mathrm{TC}(\mathcal{T}, \mathcal{CC}, x_0)$, and $\mathcal{T}(x(t_{\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1})) = \texttt{false}$. Let us rewrite these equalities in terms of the trajectories of $\mathcal{CC}_{(s,\mathcal{P}_I)}$. From equation (3), one can write $x^{[i]}(t_k) = x^{[i]}(h_{F(k)}(t_{F(k)})) = \tilde{x}^{[i]}(t_{F(k)})$, for all $i \in I$ and $k \in \mathbb{N}_0$. Therefore, we have

$$\mathcal{T}(\tilde{x}(t_{F(k)})) = \mathcal{T}(x(t_k)) = \texttt{true}\,, \qquad \text{for all } F(k) \geq F(\mathrm{TC}(\mathcal{T}, \mathcal{CC}, x_0))\,,$$
$$\mathcal{T}(\tilde{x}(t_{F(\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1)})) = \mathcal{T}(x(t_{\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1})) = \texttt{false}\,,$$

where we have used the rescheduled message-generation function in (1). Now, note that by equation (3), $\tilde{x}^{[i]}(t_\ell) = \tilde{x}^{[i]}(t_{F(\lfloor \ell/s \rfloor -1)+1})$, for all $\ell \in \mathbb{N}_0$ and all $i \in I$. Therefore, $\mathcal{T}(\tilde{x}(t_{F(\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1)+1})) = \mathcal{T}(\tilde{x}(t_{F(\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0))}))$ and we can rewrite the previous identities as

$$\mathcal{T}(\tilde{x}(t_k)) = \texttt{true}\,, \quad \text{for all } k \geq F(\mathrm{TC}(\mathcal{T}, \mathcal{CC}, x_0) - 1) + 1\,,$$
$$\mathcal{T}(\tilde{x}(t_{F(\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1)})) = \texttt{false}\,,$$

which imply that $\mathrm{TC}(\mathcal{T}, \mathcal{CC}_{(s,\mathcal{P}_I)}, x_0) = F(\mathrm{TC}(\mathcal{T}, \mathcal{CC}, x_0) - 1) + 1 = s\,\mathrm{TC}(\mathcal{T}, \mathcal{CC}, x_0)$. As for the mean communication complexity, additivity of $\mathrm{C}_{\mathrm{rnd}}$ implies

$$\mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_\ell, x(t_\ell)) = \mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_{F(\ell)-s+1}, \tilde{x}(t_{F(\ell)-s+1})) + \cdots + \mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_{F(\ell)}, \tilde{x}(t_{F(\ell)}))\,,$$

where we have used $F(\ell - 1) + 1 = F(\ell) - s + 1$. We conclude the proof by computing

$$\begin{aligned} \sum_{\ell=0}^{\mathrm{TC}(\mathcal{T},\mathcal{CC}_{(s,\mathcal{P}_I)},x_0)-1} \mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_\ell, \tilde{x}(t_\ell)) &= \sum_{\ell=0}^{F(\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1)} \mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_\ell, \tilde{x}(t_\ell)) \\ &= \sum_{\ell=0}^{\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1} \sum_{k=F(\ell)-s+1}^{F(\ell)} \mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_k, \tilde{x}(t_k)) = \sum_{\ell=0}^{\mathrm{TC}(\mathcal{T},\mathcal{CC},x_0)-1} \mathrm{C}_{\mathrm{rnd}} \circ \mathcal{M}(t_\ell, x(t_\ell))\,. \end{aligned}$$

■

Remark III.11 (Appropriate complexity notions for driftless agents) Given the results in the previous theorem, one should be careful in choosing what notion of communication complexity to evaluate control and communication laws. For driftless physical agents, rather than the *mean* communication complexity MCC, one should really consider the *total* communication complexity TCC, since the latter is invariant with respect to rescheduling. Note that the notion of infinite-horizon mean communication complexity $\mathrm{IH\text{-}MCC}$ defined in Remark III.7 satisfies the same relationship as MCC, that is, $\mathrm{IH\text{-}MCC}(\mathcal{CC}_{(s,\mathcal{P}_I)}, x_0) = \frac{1}{s}\,\mathrm{IH\text{-}MCC}(\mathcal{CC}, x_0)$. •

IV. Agreement on direction of motion and equidistance

From Examples II.3, II-C and III.3, recall the definition of uniform network $\mathcal{S}_{\text{circle}}$ of locally-connected first-order agents in $\mathbb{S}^1$, the agree-and-pursue control and communication law $\mathcal{CC}_{\text{agr-pursuit}}$, and the two coordination tasks $\mathcal{T}_{\texttt{drctn}}$ and $\mathcal{T}_{\varepsilon\text{-eqdstnc}}$. The following result characterizes the complexity to achieve these coordination tasks with $\mathcal{CC}_{\text{agr-pursuit}}$.

Theorem IV.1 (Time complexity of agree-and-pursue law) *For $k_{\text{prop}} \in]0, \frac{1}{2}[$, $r \in]0, 2\pi]$, $\alpha = Nr - 2\pi$ and $\varepsilon \in]0, 1[$, the network $\mathcal{S}_{\text{circle}}$, the law $\mathcal{CC}_{\text{agr-pursuit}}$, and the tasks $\mathcal{T}_{\texttt{drctn}}$ and $\mathcal{T}_{\varepsilon\text{-eqdstnc}}$ together satisfy:*

(i) *the bound $\mathrm{TC}(\mathcal{T}_{\texttt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in \Theta(r^{-1})$;*

(ii) *if $\alpha > 0$, the upper bound $\mathrm{TC}(\mathcal{T}_{\varepsilon\text{-eqdstnc}}, \mathcal{CC}_{\text{agr-pursuit}}) \in O(N^2 \log(N\varepsilon^{-1}) + N \log \alpha^{-1})$ and the lower bound $\mathrm{TC}(\mathcal{T}_{\varepsilon\text{-eqdstnc}}, \mathcal{CC}_{\text{agr-pursuit}}) \in \Omega(N^2 \log(\varepsilon^{-1}))$. If $\alpha \leq 0$, then $\mathcal{CC}_{\text{agr-pursuit}}$ does not achieve $\mathcal{T}_{\varepsilon\text{-eqdstnc}}$ in general.*

(These estimates are to be understood as $N \to +\infty$, $\varepsilon \to 0^+$, $r \to 0^+$, and for any possible limit of $\alpha = Nr - 2\pi$.)

Proof: In the following four *STEPS* we prove the four bounds. *STEP 1:* We start by proving the upper bound in (i). We reason by induction on the number of agents N. If $N = 1$, the result is trivially true. Assume then that the result is true for $N-1$ and let us prove it for N. Without loss of generality, assume $\texttt{drctn}^{[N]}(0) = \texttt{c}$, and that $\mathcal{T}_{\texttt{drctn}}$ is $\texttt{false}$ at time 0 (otherwise, we have finished). Therefore, at least one agent is moving counterclockwise at time 0, and we can define $k = \max\{i \in I \mid \texttt{drctn}^{[i]}(0) = \texttt{cc}\}$. Define $t_k = \inf(\{\ell \in \mathbb{N}_0 \mid \texttt{drctn}^{[k]}(\ell) = \texttt{c}\} \cup \{+\infty\})$. In what follows we provide an upper bound on t_k. For $\ell < t_k$, define

$$j(\ell) = \operatorname{argmin}\{\mathrm{dist}_{\texttt{c}}(\theta^{[i]}(\ell), \theta^{[k]}(\ell)) \mid \texttt{prior}^{[i]}(\ell) = N,\, i \in I\}.$$

In other words, for all instants of time when agent k is moving counterclockwise, the agent $j(l)$ has `prior` equal to N, is moving clockwise, and is the agent closest to agent k with these two properties. Clearly,

$$2\pi > \mathrm{dist}_{\mathtt{c}}(\theta^{[N]}(0), \theta^{[k]}(0)) = \mathrm{dist}_{\mathtt{c}}(\theta^{[j(0)]}(0), \theta^{[k]}(0)).$$

Additionally, for $\ell < t_k - 1$, we claim that

$$\mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[j(\ell+1)]}(\ell+1)) \geq k_{\text{prop}} r.$$

This happens because either (1) there is no agent clockwise-ahead of $\theta^{[j(\ell)]}(\ell)$ within clockwise distance r and, therefore, the claim is obvious, or (2) there are such agents. In case (2), let m denote the agent whose clockwise distance to agent $j(\ell)$ is maximal within the set of agents with clockwise distance r from $\theta^{[j(\ell)]}(\ell)$. Then,

$$\begin{aligned}
\mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[j(\ell+1)]}(\ell+1)) &= \mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[m]}(\ell+1)) \\
&= \mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[m]}(\ell)) + \mathrm{dist}_{\mathtt{c}}(\theta^{[m]}(\ell), \theta^{[m]}(\ell+1)) \\
&\geq \mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[m]}(\ell)) + k_{\text{prop}}\big(r - \mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[m]}(\ell))\big) \\
&= k_{\text{prop}} r + (1 - k_{\text{prop}})\, \mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[m]}(\ell)) \ \geq k_{\text{prop}} r,
\end{aligned}$$

where the first inequality follows from the fact that at time ℓ there can be no agent whose clockwise distance to agent m is less than $(r - \mathrm{dist}_{\mathtt{c}}(\theta^{[j(\ell)]}(\ell), \theta^{[m]}(\ell)))$. In summary, either agent k changes direction of motion or at each instant of time its distance to the closest agent with `prior` equal to N decreases by $k_{\text{prop}} r$. This implies

$$t_k \leq \frac{2\pi}{k_{\text{prop}}} r^{-1}.$$

Now, we distinguish two cases: (a) $k = N-1$, and (b) $k < N-1$. In case (a), after $t_{N-1} \leq \frac{2\pi}{k_{\text{prop}}} r^{-1}$ steps, the agent $N-1$ moves in the clockwise direction and has $\mathtt{prior}^{[N-1]}(t_{N-1}) = N$. In the remainder of the evolution, the message `prior` $= N$ travels faster throughout the network composed of N agents than if only agents with identities in $\{1, \dots, N-1\}$ were present. Therefore, by the induction hypothesis, $\mathrm{TC}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in O(r^{-1})$. In case (b), the message `prior` $= N$ travels faster throughout the network composed of N agents than if only agents with identities in $\{1, \dots, N-2\} \cup \{N\}$ were present. Again by the induction hypothesis, we conclude $\mathrm{TC}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in O(r^{-1})$.

STEP 2: We now prove the lower bound in (i). If $r > \pi$, then $\frac{1}{r} < \frac{1}{\pi}$, and the upper bound reads $\mathrm{TC}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in O(1)$. Obviously, the time complexity of any evolution with an initial configuration where $\mathtt{drctn}^{[i]}(0) = \mathtt{cc}$ for $i \in \{1, \dots, N-1\}$, $\mathtt{drctn}^{[N]}(0) = \mathtt{c}$ and $E_{r\text{-disk}}(\theta^{[1]}(0), \dots, \theta^{[N]}(0))$ is the complete graph, is lower bounded by 1.

Therefore, $\mathrm{TC}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in \Omega(1)$. Since $r > \pi$, we conclude $\mathrm{TC}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in \Theta(r^{-1})$. Assume then $r \leq \pi$. Consider an initial configuration where $\mathtt{drctn}^{[i]}(0) = \mathtt{cc}$ for $i \in \{1, \dots, N-1\}$, $\mathtt{drctn}^{[N]}(0) = \mathtt{c}$, and the agents are placed as depicted in Figure 3. Note that the displacement of each agent is upper bounded by

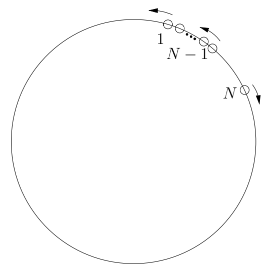

Fig. 3. Initial condition for the lower bound for $\mathrm{TC}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}})$, with $0 < \mathrm{dist}_{\mathtt{c}}(\theta^{[N-1]}(0), \theta^{[N]}(0)) - r < \varepsilon$ and $\mathrm{dist}_{\mathtt{c}}(\theta^{[1]}(0), \theta^{[N-1]}(0)) \leq r - \varepsilon$, for some fixed $\varepsilon > 0$.

$k_{\text{prop}} r \leq \frac{r}{2}$. Therefore, the number of time steps that takes agent 1 to receive the message $\mathtt{prior} = N$ is lower bounded by $\lfloor \frac{2\pi}{r} - 2 \rfloor$. We conclude $\mathrm{TC}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in \Omega(r^{-1})$.

STEP 3: We now prove the upper bound in (ii). We assume that $\mathcal{T}_{\mathtt{drctn}}$ has been achieved (so that all agents are moving clockwise), and we first prove a fact regarding connectivity. At time $\ell \in \mathbb{N}_0$, let $H(\ell)$ be the union of all the empty "circular segments" of length at least r, that is, let

$$H(\ell) = \big\{ x \in \mathbb{S}^1 \mid \min_{i \in I} \mathrm{dist}_{\mathtt{c}}(x, \theta^{[i]}(\ell)) \, + \, \min_{j \in I} \mathrm{dist}_{\mathtt{cc}}(x, \theta^{[j]}(\ell)) > r \big\}.$$

In other words, $H(\ell)$ does not contain any point between two agents separated by a distance less than r, and each connected component of $H(\ell)$ has length at least r. Let $n_H(\ell)$ be the number of connected components of $H(\ell)$, if $H(\ell)$ is empty, then we take the convention that $n_H(\ell) = 0$. Clearly, $n_H(\ell) \leq N$. We claim that, if $n_H(\ell) > 0$, then $t \mapsto n_H(\ell + t)$ is non-increasing. Let $d(\ell) < r$ be the distance between any two consecutive agents at time ℓ. Because both agents move in the same direction, a simple calculation shows that

$$d(\ell+1) \leq d(\ell) + k_{\text{prop}}(r - d(\ell)) = (1 - k_{\text{prop}}) d(\ell) + k_{\text{prop}} r < (1 - k_{\text{prop}}) r + k_{\text{prop}} r = r.$$

This means that the two agents remain within distance r and, therefore connected, at the following time instant. Because the number of connected components of $E_r(\theta^{[1]}, \dots, \theta^{[N]})$ does not increase, it follows that the number of connected components of H cannot increase. Next we claim that, if $n_H(\ell) > 0$, then there exists $t > \ell$ such that $n_H(t) < n_H(\ell)$. By contradiction, assume $n_H(\ell) = n_H(t)$ for all $t > \ell$. Without loss of generality, let $\{1, \dots, m\}$ be a set of agents with the properties that $\mathrm{dist}_{\mathtt{cc}}\left(\theta^{[i]}(\ell), \theta^{[i+1]}(\ell)\right) \leq r$, for $i \in \{1, \dots, m\}$, that $\theta^{[1]}(\ell)$ and $\theta^{[m]}(\ell)$

belong to the boundary of $H(\ell)$, and that there is no other set with the same properties and more agents. (Note that this implies that the agents $1,\dots,m$ are in counterclockwise order.) One can show that, for $t \geq \ell$,

$$\theta^{[1]}(t+1) = \theta^{[1]}(t) - k_{\text{prop}} r,$$

$$\theta^{[i]}(t+1) = \theta^{[i]}(t) - k_{\text{prop}} \operatorname{dist}_{\mathsf{c}}(\theta^{[i]}(t), \theta^{[i-1]}(t)), \quad i \in \{2,\dots,m\}.$$

If we define $d(t) = \big(\operatorname{dist}_{\mathsf{cc}}(\theta^{[1]}(t),\theta^{[2]}(t)),\dots,\operatorname{dist}_{\mathsf{cc}}(\theta^{[m-1]}(t),\theta^{[m]}(t))\big) \in \mathbb{R}^{m-1}_{>0}$, then the previous equations can be rewritten as

$$d(t+1) = \operatorname{Trid}_{m-1}(k_{\text{prop}}, 1-k_{\text{prop}}, 0)\, d(t) + r[k_{\text{prop}},\ 0,\ \cdots,\ 0]^T,$$

where the linear map $(a,b,c) \mapsto \operatorname{Trid}_{m-1}(a,b,c) \in \mathbb{R}^{(m-1)\times(m-1)}$ is defined in Appendix A. This is a discrete-time affine time-invariant dynamical system with unique equilibrium point $r(1,\dots,1)$. By Theorem A.3(ii) in Appendix A, for $\eta \in]0,1[$, the solution $t \mapsto d(t)$ to this system reaches a ball of radius η centered at the equilibrium point in time $O(m\log m + \log \eta^{-1})$. (Here we used the fact that the initial condition of this system is bounded.) In turn, this implies that $t \mapsto \sum_{i=1}^m d_i(t)$ is larger than $(m-1)(r-\eta)$ in time $O(m \log m + \log \eta^{-1})$. We are now ready to find the contradiction and show that $n_H(t)$ cannot remain equal to $n_H(\ell)$ for all time t. After time $O(m\log m + \log\eta^{-1}) = O(N \log N + \log \eta^{-1})$, we have:

$$2\pi \geq n_H(\ell) r + \sum_{j=1}^{n_H(\ell)} (r-\eta)(m_j - 1) = n_H(\ell) r + (N - n_H(\ell))(r-\eta) = n_H(\ell)\eta + N(r-\eta).$$

Here $m_1,\dots,m_{n_H(\ell)}$ are the number of agents in each isolated group, and each connected component of $H(\ell)$ has length at least r. Now, take $\eta = \frac{Nr-2\pi}{N} = \frac{\alpha}{N}$, and the contradiction follows from

$$2\pi \geq n_H(\ell)\eta + Nr - N\eta = n_H(\ell)\eta + Nr + 2\pi - Nr = n_H(\ell)\eta + 2\pi.$$

In summary this shows that, in time $O(N\log N + \log\eta^{-1}) = O(N \log N + \log \alpha^{-1})$, the number of connected components of H will decrease by one. Therefore, in time $O(N^2 \log N + N \log \alpha^{-1})$ the set H will become empty. At that time, the resulting network will obey the discrete-time linear time-invariant dynamical system:

$$d(t+1) = \operatorname{Circ}_N(k_{\text{prop}}, 1-k_{\text{prop}}, 0)\, d(t). \tag{4}$$

Here $d(t) = \big(\operatorname{dist}_{\mathsf{cc}}(\theta^{[1]}(t),\theta^{[2]}(t)),\dots,\operatorname{dist}_{\mathsf{cc}}(\theta^{[N]}(t),\theta^{[N+1]}(t))\big) \in \mathbb{R}^{N}_{>0}$, with the convention $\theta^{[N+1]} = \theta^{[1]}$. By Theorem A.3(iii) in Appendix A, in time $O\big(N^2 \log \varepsilon^{-1}\big)$, the error 2-norm satisfies the contraction inequality $\|d(\ell) - d_*\|_2 \leq \varepsilon \|d(0) - d_*\|_2$, for $d_* = \frac{2\pi}{N}\mathbf{1}$. We convert this inequality on 2-norms into an appropriate inequality on ∞-norms as follows. Note that $\|d(0) - d_*\|_\infty = \max_{i \in I} |d^{[i]}(0) - d_*^{[i]}| \leq 2\pi$. For ℓ of order $N^2 \log \eta^{-1}$,

$$\|d(\ell) - d_*\|_\infty \leq \|d(\ell) - d_*\|_2 \leq \eta \|d(0) - d_*\|_2 \leq \eta\sqrt{N}\|d(0) - d_*\|_\infty \leq \eta 2\pi \sqrt{N}.$$

This means that the desired configuration is achieved for $\eta 2\pi\sqrt{N} = \varepsilon$, that is, in time $O(N^2 \log \eta^{-1}) = O(N^2 \log(N\varepsilon^{-1}))$. In summary, the equidistance task is achieved in time $O(N^2 \log(N\varepsilon^{-1}) + N \log \alpha^{-1})$.

STEP 4: Finally, we prove the lower bound in (ii). We consider an initial configuration with the properties that (i) agents are counterclockwise-ordered according to their unique identifier, (ii) the set H is empty, and (iii) the inter-agent distances $d(0) = \left(\mathrm{dist}_{\mathtt{cc}}(\theta^{[1]}(0), \theta^{[2]}(0)), \dots, \mathrm{dist}_{\mathtt{cc}}(\theta^{[N]}(0), \theta^{[1]}(0))\right)$ are given by

$$d(0) = \frac{2\pi}{N}\mathbf{1} + k(\mathbf{v}_N + \overline{\mathbf{v}}_N),$$

where $\mathbf{v}_N$ is the eigenvector of $\mathrm{Circ}_N(k_{\text{prop}}, 1-k_{\text{prop}}, 0)$ corresponding to the eigenvalue $1 - k_{\text{prop}} + k_{\text{prop}} \cos\left(\frac{2\pi}{N}\right) - k_{\text{prop}}\sqrt{-1}\sin\left(\frac{2\pi}{N}\right)$ (see Appendix A), and $k_{\text{prop}} > 0$ is chosen sufficiently small so that $d(0) \in \mathbb{R}^N_{>0}$. By Theorem A.3(iii) in Appendix A, the solution $t \mapsto d(t)$ reaches the desired configuration in time $\Theta(N^2 \log \varepsilon^{-1})$ with an error whose 2-norm, and therefore, its ∞-norm is of order ε. This concludes the result. ■

To conclude this section, we study the total communication complexity of the agree-and-pursue control and communication law. We consider the case of a unidirectional communication model with one-round cost function depending linearly on the cardinality of the communication graph. Because it is always true that $\mathrm{TCC}(\mathcal{T}, \mathcal{CC}) \leq \mathrm{MCC}(\mathcal{T}, \mathcal{CC}) \cdot \mathrm{TC}(\mathcal{T}, \mathcal{CC})$ and because of Theorem IV.1, we deduce the following bounds

$$\mathrm{TCC}_{\mathrm{unidir}}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) \in O(N^2 r^{-1}),$$

$$\mathrm{TCC}_{\mathrm{unidir}}(\mathcal{T}_{\varepsilon\text{-eqdstnc}}, \mathcal{CC}_{\text{agr-pursuit}}) \in O(N^4 \log(N\varepsilon^{-1}) + N^3 \log \alpha^{-1}),$$

since the number of edges in $E_{r\text{-disk}}$ is in $O(N^2)$. The next result gives a more accurate estimate.

Theorem IV.2 (Total communication complexity of agree-and-pursue law) *For $k_{\text{prop}} \in]0, \frac{1}{2}[$, $r \in]0, 2\pi]$, $\alpha = Nr - 2\pi$ and $\varepsilon \in]0, 1[$, the network $\mathcal{S}_{\text{circle}}$, the law $\mathcal{CC}_{\text{agr-pursuit}}$, and the tasks $\mathcal{T}_{\mathtt{drctn}}$ and $\mathcal{T}_{\varepsilon\text{-eqdstnc}}$ together satisfy:*

(i) *the bound $\mathrm{TCC}_{\mathrm{unidir}}(\mathcal{T}_{\mathtt{drctn}}, \mathcal{CC}_{\text{agr-pursuit}}) = \Theta(N^2 r^{-1})$;*

(ii) *if $\alpha > 0$, the upper bound $\mathrm{TCC}_{\mathrm{unidir}}(\mathcal{T}_{\varepsilon\text{-eqdstnc}}, \mathcal{CC}_{\text{agr-pursuit}}) \in O((\alpha+1)N^2(N \log N + \log \alpha^{-1}) + N^4 \log(\varepsilon^{-1}))$ and the lower bound $\Omega(N^3 \alpha \log \varepsilon^{-1})$.*

(These estimates are to be understood as $N \to +\infty$, $\varepsilon \to 0^+$, $r \to 0^+$, and for any possible limit of $\alpha = Nr - 2\pi$.)

Proof: We follow the steps and notation in the proof of Theorem IV.1. The lower bound in (i) can be readily deduced by examining the evolution of the two initial configurations employed in the proof of Theorem IV.1 to prove the lower bound on the time complexity. Regarding (ii), let us consider first the case when $n_H(0) = 0$. In this case, the network obeys the discrete-time linear time-invariant dynamical system (4). By Theorem A.3(iii) in Appendix A, the desired configuration is reached in time $\Theta(N^2 \log \varepsilon^{-1})$ with an error whose 2-norm, and therefore, its ∞-norm is of order ε. In this case, one can see that the number of edges in $E_{r\text{-disk}}$ is upper bounded by $O(N^2)$ and lower bounded by $\Omega(\alpha N)$. From here, we deduce the upper bound $O(N^4 \log \varepsilon^{-1})$ and the lower bound $\Omega(N^3 \alpha \log \varepsilon^{-1})$ on the total communication complexity.

Consider now the case when $n_H(0) > 0$. Let t_* be the time it takes the network to reduce the number of connected components of H to $n_H(0) - 1$. We treat the two possible situations (i) $t_* \in \Theta(N \log N + \log \alpha^{-1})$ and (ii) $t_* \ll \Theta(N \log N + \log \alpha^{-1})$. In the case (i), each isolated group of agents reaches a ball of radius $\eta = \frac{\alpha}{N}$ centered at the equilibrium point $r(1, \dots, 1)$. Up to t_*, the total communication complexity is then upper bounded by $O(N^3 \log N + N^2 \log \alpha^{-1})$. After time t_*, each agent has $O(\alpha)$ neighbors, and therefore we obtain the following upper bound on the total communication complexity

$$O(N^3 \alpha \log N + N^2 \alpha \log \alpha^{-1})$$

up to the instant when the set H becomes empty. In the case (ii), let us redefine t_* to be the time it takes the network to reduce the number of connected components of H to $n_H(0) - 2$. Again, either (i) or (ii) might hold true for t_*. Proceeding inductively, we only have to upper bound the total communication complexity when t_* keeps falling in case (ii). In this situation, one can bound the total communication complexity up to the instant when the set H becomes empty by $O(N^3 \log N + N^2 \log \alpha^{-1})$. The statement of the theorem then follows. ∎

Remark IV.3 (Comparison with leader election) Let us compare the agree-and-pursue control and communication law with the classical Lann-Chang-Roberts (LCR) algorithm for leader election (see [3, Chapter 3.3]). The leader election coordination task consists of electing a unique agent among all agents in the network. It is therefore slightly different from, but closely related to, the coordination task $\mathcal{T}_{\mathtt{drctn}}$. The LCR algorithm operates on a static network with the ring communication topology, and achieves leader election with time and total communication complexity, respectively, $\Theta(N)$ and $\Theta(N^2)$. The agree-and-pursue law operates on a robotic network with the r-disk communication topology, and achieves $\mathcal{T}_{\mathtt{drctn}}$ with time and total communication complexity, respectively, $\Theta(r^{-1})$ and $\Theta(N^2 r^{-1})$. Interestingly, the mobility of the network together with the richer communication topology speeds up the completion of the task, without compromising the total communication complexity. •

V. Conclusions

We have introduced a formal model for the design and analysis of coordination algorithms executed by networks composed of robotic agents. In this framework motion coordination algorithms are formalized as feedback control and communication laws. Drawing analogies with the discipline of distributed algorithms, we have defined two measures of complexity for control and communication laws: the time and the mean communication complexity of achieving a specific task. We have defined the notion of re-scheduling of a control and communication law and analyzed the invariance of the proposed complexity measures under this operation. These concepts and results are illustrated in a network of locally connected agents on the circle executing a novel "agree-and-pursue" motion coordination algorithm that combines elements of the leader election and cyclic pursuit problems.

The proposed notions allow us to compare the scalability properties of different coordination algorithms with regards to performance and communication costs. Numerous avenues for future research appear open. An incomplete list include: (i) modeling of asynchronous networks (see however [21], [22], [7]); (ii) robustness analysis with respect to failures in the agents (arrivals/departures) and in the communication links (see however [16], [23], [24], [25]); (iii) probabilistic versions of the complexity measures that capture, for instance, the expected performance and cost of coordination algorithms (see however [9]); (iv) quantization and delays in the communication channels (see however [26] and the literature on quantized control); and (v) parallel, sequential and hierarchical composition of control and communication laws. On the algorithmic side, the companion paper [14] provides time-complexity estimates for coordination algorithms that achieve rendezvous and deployment, and discusses other open questions.

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APPENDIX A

TRIDIAGONAL TOEPLITZ AND CIRCULANT DYNAMICAL SYSTEMS

This section presents some key facts about convergence rates of discrete-time dynamical systems defined by certain classes of Toeplitz matrices, see [27]. To the best of our knowledge, the results presented below in Theorems A.3 and A.4 are novel contributions; see also [13], [28] for some related results for a different class of circulant matrices. For $N \geq 2$ and $a, b, c \in \mathbb{R}$, define the $N \times N$ Toeplitz matrices $\mathrm{Trid}_N(a,b,c)$ and $\mathrm{Circ}_N(a,b,c)$ by

$$\mathrm{Trid}_N(a,b,c) = \begin{bmatrix} b & c & 0 & \dots & 0 \\ a & b & c & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & a & b & c \\ 0 & \dots & 0 & a & b \end{bmatrix}, \qquad \mathrm{Circ}_N(a,b,c) = \mathrm{Trid}_N(a,b,c) + \begin{bmatrix} 0 & \dots & \dots & 0 & a \\ 0 & \dots & \dots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & \dots & 0 & 0 \\ c & 0 & \dots & 0 & 0 \end{bmatrix}.$$

The matrices Trid_N and Circ_N are tridiagonal and circulant, respectively. The two matrices only differ in their $(1, N)$ and $(N, 1)$ entries. Note our convention that $C_2(a,b,c) = \begin{bmatrix} b & a+c \\ a+c & b \end{bmatrix}$. The following results are discussed, for example, in [27, Example 7.2.5 and Exercise 7.2.20].

Lemma A.1 (Eigenvalues of tridiagonal Toeplitz and circulant matrices) *For $N \geq 2$ and $a, b, c \in \mathbb{R}$, the following statements hold:*

(i) *for* $ac \neq 0$*, the eigenvalues and eigenvectors of* $\mathrm{Trid}_N(a,b,c)$ *are, for* $i \in \{1,\dots,N\}$*,*

$$b+2c\sqrt{\frac{a}{c}}\cos\left(\frac{i\pi}{N+1}\right), \quad \left[\left(\frac{a}{c}\right)^{1/2}\sin\left(\frac{i\pi}{N+1}\right), \quad \left(\frac{a}{c}\right)^{2/2}\sin\left(\frac{2i\pi}{N+1}\right), \quad \dots, \quad \left(\frac{a}{c}\right)^{N/2}\sin\left(\frac{Ni\pi}{N+1}\right)\right]^T;$$

(ii) *the eigenvalues and eigenvectors of* $\mathrm{Circ}_N(a,b,c)$ *are, for* $\omega = \exp(\frac{2\pi\sqrt{-1}}{N})$ *and for* $i \in \{1,\dots,N\}$*,*

$$b+(a+c)\cos\left(\frac{i2\pi}{N}\right)+\sqrt{-1}(c-a)\sin\left(\frac{i2\pi}{N}\right), \quad \textit{and} \quad \left[1,\ \omega^i,\ \cdots,\ \omega^{(N-1)i}\right]^T. \qquad \bullet$$

Remarks A.2 (i) The set of eigenvalues of $\mathrm{Trid}_N(a,b,c)$ is contained in the real interval $[b-2\sqrt{ac}, b+2\sqrt{ac}]$, if $ac \geq 0$, and in the interval in the complex plane $[b-2\sqrt{-1}\sqrt{|ac|}, b+2\sqrt{-1}\sqrt{|ac|}]$, if $ac \leq 0$.

(ii) The set of eigenvalues of $\mathrm{Circ}_N(a,b,c)$ is contained in the ellipse on the complex plane with center b, horizontal axis $2|a+c|$ and vertical axis $2|c-a|$.

(iii) Recall from [27] that (1) a square matrix is normal if it has a complete orthonormal set of eigenvectors, (2) circulant matrices and real-symmetric matrices are normal, and (3) if a normal matrix has eigenvalues $\{\lambda_1,\dots,\lambda_n\}$, then its singular values are $\{|\lambda_1|,\dots,|\lambda_n|\}$. $\bullet$

We can now state the main result of this section.

Theorem A.3 (Tridiagonal Toeplitz and circulant dynamical systems) *Let* $N \geq 2$*,* $\varepsilon \in]0,1[$*, and* $a,b,c \in \mathbb{R}$*. Let* $x\colon \mathbb{N}_0 \to \mathbb{R}^N$ *and* $y\colon \mathbb{N}_0 \to \mathbb{R}^N$ *be solutions to*

$$x(\ell+1) = \mathrm{Trid}_N(a,b,c)\,x(\ell), \qquad y(\ell+1) = \mathrm{Circ}_N(a,b,c)\,y(\ell),$$

with initial conditions $x(0)=x_0$ *and* $y(0)=y_0$*, respectively. The following statements hold:*

(i) *if* $a = c \neq 0$ *and* $|b|+2|a| = 1$*, then* $\lim_{\ell\to+\infty} x(\ell) = \mathbf{0}$*, and the maximum time required for* $\|x(\ell)\|_2 \leq \varepsilon\|x_0\|_2$ *(over all initial conditions* $x_0 \in \mathbb{R}^N$*) is* $\Theta\big(N^2\log\varepsilon^{-1}\big)$*;*

(ii) *if* $a \neq 0$*,* $c = 0$ *and* $0 < |b| < 1$*, then* $\lim_{\ell\to+\infty} x(\ell) = \mathbf{0}$*, and the maximum time required for* $\|x(\ell)\|_2 \leq \varepsilon\|x_0\|_2$ *(over all initial conditions* $x_0 \in \mathbb{R}^N$*) is* $O\big(N\log N + \log\varepsilon^{-1}\big)$*;*

(iii) *if* $a \geq 0$*,* $c \geq 0$*,* $b > 0$*, and* $a+b+c = 1$*, then* $\lim_{\ell\to+\infty} y(\ell) = y_{\text{ave}}\mathbf{1}$*, where* $y_{\text{ave}} = \frac{1}{N}\mathbf{1}^T y_0$*, and the maximum time required for* $\|y(\ell) - y_{\text{ave}}\mathbf{1}\|_2 \leq \varepsilon\|y_0 - y_{\text{ave}}\mathbf{1}\|_2$ *(over all initial conditions* $y_0 \in \mathbb{R}^N$*) is* $\Theta\big(N^2\log\varepsilon^{-1}\big)$*.* $\bullet$

Proof: Let us prove fact (i). We start by bounding from above the eigenvalue with largest absolute value, that is, the largest singular value, of $\mathrm{Trid}_N(a,b,a)$:

$$\max_{i\in\{1,\dots,N\}}\left|b+2a\cos\left(\frac{i\pi}{N+1}\right)\right| \leq |b|+2|a|\max_{i\in\{1,\dots,N\}}\left|\cos\left(\frac{i\pi}{N+1}\right)\right| \leq |b|+2|a|\cos\left(\frac{\pi}{N+1}\right).$$

Because $\cos(\frac{\pi}{N+1}) < 1$ for any $N \geq 2$, the matrix $\mathrm{Trid}_N(a,b,a)$ is stable. Additionally, for $\ell > 0$, we bound from above the magnitude of the curve x as

$$\|x(\ell)\|_2 = \|\,\mathrm{Trid}_N(a,b,a)^\ell x_0\|_2 \leq \left(|b| + 2|a|\cos\left(\frac{\pi}{N+1}\right)\right)^\ell \|x_0\|_2.$$

In order to have $\|x(\ell)\|_2 < \varepsilon\|x_0\|_2$, it is sufficient that $\ell \log\left(|b| + 2|a|\cos\left(\frac{\pi}{N+1}\right)\right) < \log\varepsilon$, that is

$$\ell > \frac{\log\varepsilon^{-1}}{-\log\left(|b| + 2|a|\cos\left(\frac{\pi}{N+1}\right)\right)}. \tag{A.5}$$

To show the upper bound, note that as $t \to 0$ we have

$$-\frac{1}{\log(1 - 2|a|(1-\cos t))} = \frac{1}{|a|t^2} + O(1).$$

Now, assume without loss of generality that $ab > 0$ and consider the eigenvalue $b + 2a\cos(\frac{\pi}{N+1})$ of $\mathrm{Trid}_N(a,b,a)$. Note that $|b + 2a\cos(\frac{\pi}{N+1})| = |b| + 2|a|\cos(\frac{\pi}{N+1})$. (If $ab < 0$, then consider the eigenvalue $b + 2a\cos(\frac{N\pi}{N+1})$.) For $N > 2$, define the unit-length vector

$$\mathbf{v}_N = \sqrt{\frac{2}{N+1}}\Big[\sin\frac{\pi}{N+1},\ \cdots,\ \sin\frac{N\pi}{N+1}\Big]^T \in \mathbb{R}^N, \tag{A.6}$$

and note that, by Lemma A.1(i), $\mathbf{v}_N$ is an eigenvector of $\mathrm{Trid}_N(a,b,a)$ with eigenvalue $b + 2a\cos(\frac{\pi}{N+1})$. Note also that all components of $\mathbf{v}_N$ are positive. The trajectory x with initial condition $\mathbf{v}_N$ satisfies $\|x(\ell)\|_2 = \left(|b| + 2|a|\cos\left(\frac{\pi}{N+1}\right)\right)^\ell \|\mathbf{v}_N\|_2$ and, therefore, it will enter $B(\mathbf{0}, \varepsilon\|\mathbf{v}_N\|_2)$ only when ℓ satisfies (A.5). This completes the proof of fact (i).

Next we consider statement (ii). Clearly, $\mathrm{Trid}_N(a,b,0)$ is stable. For $\ell > 0$, we compute

$$\mathrm{Trid}_N(a,b,0)^\ell = b^\ell\Big(I_N + \frac{a}{b}\,\mathrm{Trid}_N(1,0,0)\Big)^\ell = b^\ell \sum_{j=0}^{N-1} \frac{\ell!}{j!(\ell-j)!}\Big(\frac{a}{b}\Big)^j \mathrm{Trid}_N(1,0,0)^j$$

because of the nilpotency of $\mathrm{Trid}_N(1,0,0)$. Now we can bound from above the magnitude of the curve x as

$$\begin{aligned}\|x(\ell)\|_2 = \|\,\mathrm{Trid}_N(a,b,0)^\ell x_0\|_2 &\leq |b|^\ell \sum_{j=0}^{N-1} \frac{\ell!}{j!(\ell-j)!}\Big(\frac{a}{b}\Big)^j \big\|\,\mathrm{Trid}_N(1,0,0)^j x_0\big\|_2 \\ &\leq \mathrm{e}^{a/b}\ell^{N-1}\,|b|^\ell\,\|x_0\|_2.\end{aligned}$$

Here we used $\|\,\mathrm{Trid}_N(1,0,0)^j x_0\|_2 \leq \|x_0\|_2$ and $\max\{\frac{\ell!}{(\ell-j)!} \mid j \in \{0,\dots,N-1\}\} \leq \ell^{N-1}$. Therefore, in order to have $\|x(\ell)\|_2 < \varepsilon\|x_0\|_2$, it suffices that $\log(\mathrm{e}^{a/b}) + (N-1)\log\ell + \ell\log|b| \leq \log\varepsilon$, that is

$$\ell - \frac{N-1}{-\log|b|}\log\ell > \frac{\frac{a}{b} - \log\varepsilon}{-\log|b|}.$$

A sufficient condition for $\ell - \alpha \log \ell > \beta$, for $\alpha, \beta > 0$, is that $\ell \geq 2\beta + 2\alpha \max\{1, \log \alpha\}$. For, if $\ell \geq 2\alpha$, then $\log \ell$ is bounded from above by the line $\ell/2\alpha + \log \alpha$. Furthermore, the line $\ell/2\alpha + \log \alpha$ is a lower bound for the line $(\ell - \beta)/\alpha$ if $\ell \geq 2\beta + 2\alpha \log \alpha$. In summary, it is true that $\|x(\ell)\|_2 \leq \varepsilon \|x(0)\|_2$ whenever

$$\ell \geq 2 \frac{\frac{a}{b} - \log \varepsilon}{-\log |b|} + 2 \frac{N-1}{-\log |b|} \max \left\{1, \log \frac{N-1}{-\log |b|}\right\}.$$

This completes the proof of the upper bound, that is, fact (ii).

The proof of fact (iii) is similar to that of fact (i). We analyze the singular values of $\mathrm{Circ}_N(a, b, c)$. It is clear that the eigenvalue corresponding to $i = N$ is equal to 1; this is the largest singular value of $\mathrm{Circ}_N(a, b, c)$ and the corresponding eigenvector is $\mathbf{1}$. In the orthogonal decomposition induced by the eigenvectors of $\mathrm{Circ}_N(a, b, c)$, the vector y_0 has a component y_{ave} along the eigenvector $\mathbf{1}$. We now compute the second largest singular value:

$$\max_{i \in \{1, \dots, N-1\}} \left| b + (a+c) \cos\left(\frac{i2\pi}{N}\right) + \sqrt{-1}(c-a) \sin\left(\frac{i2\pi}{N}\right) \right| \\ = \left| 1 - (a+c)\Big(1 - \cos\big(\frac{2\pi}{N}\big)\Big) + \sqrt{-1}(c-a) \sin\left(\frac{2\pi}{N}\right) \right|.$$

Here $|\cdot|$ is the norm in $\mathbb{C}$. Because of the assumptions on a, b, c, the second largest singular value is strictly less than 1. For $\ell > 0$, we bound the distance of the curve $y(\ell)$ from $y_{\text{ave}}\mathbf{1}$ as

$$\|y(\ell) - y_{\text{ave}}\mathbf{1}\|_2 = \|\,\mathrm{Circ}_N(a, b, c)^\ell y_0 - y_{\text{ave}}\mathbf{1}\|_2 = \|\,\mathrm{Circ}_N(a, b, c)^\ell \big(y_0 - y_{\text{ave}}\mathbf{1}\big)\|_2 \\ \leq \left| 1 - (a+c)\Big(1 - \cos\big(\frac{2\pi}{N}\big)\Big) + \sqrt{-1}(c-a) \sin\left(\frac{2\pi}{N}\right) \right|^\ell \|y_0 - y_{\text{ave}}\mathbf{1}\|_2.$$

This proves that $\lim_{\ell \to +\infty} y(\ell) = y_{\text{ave}}\mathbf{1}$. Also, for $\alpha = a + c, \beta = c - a$ and as $t \to 0$, we have

$$-\frac{1}{\log\left(\big(1 - \alpha(1 - \cos t)\big)^2 + \beta^2 \sin^2 t\right)^{1/2}} = \frac{2}{(\alpha - \beta^2)t^2} + O(1).$$

Here $\beta^2 < \alpha$ because $a, c \in]0, 1[$. From this, one deduces the upper bound in (iii).

Now, consider the eigenvalues $\lambda_N = b + (a+c) \cos\left(\frac{2\pi}{N}\right) + \sqrt{-1}(c-a) \sin\left(\frac{2\pi}{N}\right)$ and $\overline{\lambda}_N = b + (a + c) \cos\left(\frac{(N-1)2\pi}{N}\right) + \sqrt{-1}(c-a) \sin\left(\frac{(N-1)2\pi}{N}\right)$ of $\mathrm{Circ}_N(a, b, c)$, and its associated eigenvectors (cf. Lemma A.1(ii))

$$\mathbf{v}_N = \Big[1,\ w,\ \cdots,\ w^{N-1}\Big]^T \in \mathbb{C}^N, \quad \overline{\mathbf{v}}_N = \Big[1,\ w^{N-1}, \cdots,\ w\Big]^T \in \mathbb{C}^N. \tag{A.7}$$

Note that the vector $\mathbf{v}_N + \overline{\mathbf{v}}_N$ belongs to $\mathbb{R}^N$. Moreover, its component y_{ave} along the eigenvector $\mathbf{1}$ is 0. The trajectory y with initial condition $\mathbf{v}_N + \overline{\mathbf{v}}_N$ satisfies $\|y(\ell)\|_2 = \|\lambda_N^\ell \mathbf{v}_N + \overline{\lambda}_N^\ell \overline{\mathbf{v}}_N\|_2 = |\lambda_N|^\ell \|\mathbf{v}_N + \overline{\mathbf{v}}_N\|_2$ and, therefore, it will enter $B(\mathbf{0}, \varepsilon \|\mathbf{v}_N + \overline{\mathbf{v}}_N\|_2)$ only when

$$\ell > \frac{\log \varepsilon^{-1}}{-\log \left| 1 - (a+c)\Big(1 - \cos\big(\frac{2\pi}{N}\big)\Big) + \sqrt{-1}(c-a) \sin\big(\frac{2\pi}{N}\big) \right|}.$$

This completes the proof of fact (iii). ■

Next, we extend these results to another interesting set of matrices. For $N \geq 2$ and $a, b \in \mathbb{R}$, define the $N \times N$ *augmented tridiagonal matrices* $\mathrm{ATrid}_N^+(a,b)$ and $\mathrm{ATrid}_N^-(a,b)$ by

$$\mathrm{ATrid}_N^{\pm}(a,b) = \mathrm{Trid}_N(a,b,a) \pm \begin{bmatrix} a & 0 & \dots & \dots & 0 \\ 0 & 0 & \dots & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & \dots & 0 & 0 \\ 0 & \dots & \dots & 0 & a \end{bmatrix}.$$

If we define

$$P_+ = \begin{bmatrix} 1 & 1 & 0 & 0 & \dots & 0 \\ 1 & -1 & 1 & 0 & \dots & 0 \\ 1 & 0 & -1 & 1 & \dots & 0 \\ \vdots & & \ddots & \ddots & \ddots & \\ 1 & 0 & \dots & 0 & -1 & 1 \\ 1 & 0 & \dots & 0 & 0 & -1 \end{bmatrix}, \qquad P_- = \begin{bmatrix} 1 & 1 & 0 & 0 & \dots & 0 \\ -1 & 1 & 1 & 0 & \dots & 0 \\ 1 & 0 & 1 & 1 & \dots & 0 \\ \vdots & & \ddots & \ddots & \ddots & \\ (-1)^{N-2} & 0 & \dots & 0 & 1 & 1 \\ (-1)^{N-1} & 0 & \dots & 0 & 0 & 1 \end{bmatrix},$$

then the following similarity transforms are satisfied:

$$\mathrm{ATrid}_N^{\pm}(a,b) = P_{\pm} \begin{bmatrix} b \pm 2a & 0 \\ 0 & \mathrm{Trid}_{N-1}(a,b,a) \end{bmatrix} P_{\pm}^{-1}, \tag{A.8}$$

To analyze the convergence properties of the dynamical systems determined by $\mathrm{ATrid}_N^+(a,b)$ and $\mathrm{ATrid}_N^-(a,b)$, we recall that $\mathbf{1}^T = (1,\dots,1) \in \mathbb{R}^N$, and we define $\mathbf{1}_- = (1,-1,1,\dots,(-1)^{N-2},(-1)^{N-1})^T \in \mathbb{R}^N$.

Theorem A.4 (Augmented tridiagonal Toeplitz dynamical systems) *Let $N \geq 2$, $\varepsilon \in]0,1[$, and $a, b \in \mathbb{R}$ with $a \neq 0$ and $|b| + 2|a| = 1$. Let $x\colon \mathbb{N}_0 \to \mathbb{R}^N$ and $z\colon \mathbb{N}_0 \to \mathbb{R}^N$ be solutions to*

$$x(\ell+1) = \mathrm{ATrid}_N^+(a,b)\, x(\ell), \qquad z(\ell+1) = \mathrm{ATrid}_N^-(a,b)\, z(\ell),$$

with initial conditions $x(0) = x_0$ and $z(0) = z_0$, respectively. The following statements hold:

(i) $\lim_{\ell\to+\infty} \big(x(\ell) - x_{\mathrm{ave}}(\ell)\mathbf{1}\big) = \mathbf{0}$, *where $x_{\mathrm{ave}}(\ell) = (\frac{1}{N}\mathbf{1}^T x_0)(b+2a)^\ell$, and the maximum time required for $\|x(\ell) - x_{\mathrm{ave}}(\ell)\mathbf{1}\|_2 \leq \varepsilon \|x_0 - x_{\mathrm{ave}}(0)\mathbf{1}\|_2$ (over all initial conditions $x_0 \in \mathbb{R}^N$) is $\Theta\big(N^2 \log \varepsilon^{-1}\big)$;*

(ii) $\lim_{\ell\to+\infty} \big(z(\ell) - z_{\mathrm{ave}}(\ell)\mathbf{1}_-\big) = \mathbf{0}$, *where $z_{\mathrm{ave}}(\ell) = (\frac{1}{N}\mathbf{1}_-^T z_0)(b-2a)^\ell$, and the maximum time required for $\|z(\ell) - z_{\mathrm{ave}}(\ell)\mathbf{1}_-\|_2 \leq \varepsilon \|z_0 - z_{\mathrm{ave}}(0)\mathbf{1}_-\|_2$ (over all initial conditions $z_0 \in \mathbb{R}^N$) is $\Theta\big(N^2 \log \varepsilon^{-1}\big)$.* •

Proof: We prove fact (i) and remark that the proof of fact (ii) is analogous. Consider the change of coordinates

$$x(\ell) = P_+ \begin{bmatrix} x'_{\mathsf{ave}}(\ell) \\ y(\ell) \end{bmatrix} = x'_{\mathsf{ave}}(\ell)\mathbf{1} + P_+ \begin{bmatrix} 0 \\ y(\ell) \end{bmatrix},$$

where $x'_{\mathsf{ave}}(\ell) \in \mathbb{R}$ and $y(\ell) \in \mathbb{R}^{N-1}$. A quick calculation shows that $x'_{\mathsf{ave}}(\ell) = \frac{1}{N}\mathbf{1}^T x(\ell)$, and the similarity transformation described in equation (A.8) implies

$$y(\ell+1) = \mathrm{Trid}_{N-1}(a,b,a)\, y(\ell), \quad \text{and} \quad x'_{\mathsf{ave}}(\ell+1) = (b+2a)x'_{\mathsf{ave}}(\ell).$$

Therefore, $x_{\mathsf{ave}} = x'_{\mathsf{ave}}$. It is also clear that

$$x(\ell+1) - x_{\mathsf{ave}}(\ell+1)\mathbf{1} = P_+ \begin{bmatrix} 0 \\ y(\ell+1) \end{bmatrix} = \left(P_+ \begin{bmatrix} 0 & 0 \\ 0 & \mathrm{Trid}_{N-1}(a,b,a) \end{bmatrix} P_+^{-1} \right) (x(\ell) - x_{\mathsf{ave}}(\ell)\mathbf{1}).$$

Consider the matrix in parenthesis determining the trajectory $\ell \mapsto (x(\ell) - x_{\mathsf{ave}}(\ell)\mathbf{1})$. This matrix is symmetric, its eigenvalues are 0 and the eigenvalues of $\mathrm{Trid}_{N-1}(a,b,a)$, and its eigenvectors are $P_+(1,0,\dots,0) \in \mathbb{R}^N$ and the eigenvectors of $\mathrm{Trid}_{N-1}(a,b,a)$, padded with an extra zero and premultiplied by P_+. These facts are sufficient to duplicate, step by step, the proof of fact (i) in Theorem A.3. Therefore, fact (i) follows. ■

We conclude this append with some useful bounds whose proof is straightforward in coordinates.

Lemma A.5 *Assume $x \in \mathbb{R}^N$, $y \in \mathbb{R}^{N-1}$ and $z \in \mathbb{R}^{N-1}$ jointly satisfy*

$$x = P_+ \begin{bmatrix} 0 \\ y \end{bmatrix}, \qquad x = P_- \begin{bmatrix} 0 \\ z \end{bmatrix}.$$

Then $\frac{1}{2}\|x\|_2 \leq \|y\|_2 \leq (N-1)\|x\|_2$ and $\frac{1}{2}\|x\|_2 \leq \|z\|_2 \leq (N-1)\|x\|_2$. •