A Project Summary

Most coordinated tasks performed by teams of mobile robots require reliable communications between the members of the team. This restricts collective robot motion to formations that guarantee *integrity of the communication network* and induces an interplay between the physical constraints on the trajectories and velocities, and the optimization of the communication variables like packet routes and transmitted powers. The development of theory and algorithms that address this interplay while ensuring a desired *system performance*, e.g., communication integrity and task completion, is, therefore, necessary to facilitate efficient design and deployment of mobile robot networks.

Objective. The goal of this project is to **develop formal methods for networks of mobile robots that integrate control in the communication and physical domains**. The key idea that motivates this research is a novel definition of network integrity that differs from existing approaches in that it is not based on proximity relations and graph theory but on metrics that are of interest to the performance of the communication between robots or between robots and a fixed infrastructure. This novel technical approach offers a number of advantages over other approaches, including more realistic models of robot networks, lower complexity compared to the combinatorial graph theoretic approaches, easiness of distributed implementation via distributed optimization and control, and possible connections with graphs and their spectral properties. In fact, if this project is successful, we will be able to revisit a number of robotic applications, currently addressed in terms of graph theory, that involve algorithms that depend on the network spectrum.

The proposed research program spans a broad range of theoretical and applied research, and it embodies a career development plan with short and long term goals. It includes the development of theoretical results and algorithms, but also emphasizes on their application in mobile robot networks and other related fields.

Intellectual Merit. The proposed research will provide a novel approach to the design and control of mobile robot networks. The intellectual merit of this research is the use of *optimal wireless network design* to develop novel control alternatives in the physical domain. This poses significant intellectual challenges related to integration and control in the cyber (communications) and physical (robots) domains. We will develop quantitative tools to address these challenges for mobile communication networks and other systems with similar network structure and objectives. This will require synthesis of new theoretical results coming from control theory, optimization, and hybrid systems theory. The proposed research points to a new direction in systems and control theory on the interface with communications and networking.

Broader Impact. The proposed research is highly relevant for most coordinated tasks performed by teams of mobile robots. Recent advances in robotics and communications can not be efficiently integrated on real platforms without the necessary theoretical and experimental support. Successful completion of this research will provide these necessary components in facilitating the design of mobile autonomous systems and fostering their adoption. Moreover, if this project is successful, we plan to extend these results to other fields facing similar control challenges. Examples include biomolecular networks, power networks, and transportation networks. The broader impact of this project lies on disseminating the research output in the industry and academia.

As an integral part to this research program, we also propose an **educational agenda** involving K-12, undergraduate and graduate level education. The broader impact of the educational program is educating the next generation of engineers and researchers that are fluent in multidisciplinary research collaborations and are aware of the tremendous potentials of such activities. The outreach component of the educational program will also improve the pre-college students' awareness of the potential and attractiveness of a research and engineering career. Additionally, we will pursue synergistic **collaborations with international institutions** in Europe to promote cross-disciplinary research over a network of young scientists and engineers spanning the United States and Europe.

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C.1 Introduction

Most coordinated tasks performed by teams of mobile robots require reliable communications between the members of the team. This restricts collective robot motion to formations that guarantee integrity of the communication network. **Our definition of network integrity differs from existing approaches in that it is not based on proximity relations and graph theory but on metrics that are of interest to the performance of the communication between robots or between robots and a fixed infrastructure.** Rather than constraining motion to achieve a connected topology in a graph theoretic sense, motion is constrained to achieve, e.g., target end-to-end communication rates or given delay constraints. Ensuring network integrity induces an interplay between physical constraints on the trajectories and velocities, and optimization of the communication variables like packet routes and transmitted powers.

To conceptualize the proposed research, consider a team of mobile robots in a surveillance mission, that carry audio and video sensors used to locate intruders from sound and image (Fig. 1). The robots have limited communication capabilities due to power constraints and environmental interference, so this information is propagated back to the user via a multi-hop communication network. Optimal operating points of the network need to be determined, that satisfy a number of constraints that ensure consistency of the operating points, as well as external constraints like minimum guaranteed throughputs for audio and visual data or maximum power consumptions. Variables of this optimization typically depend on the robot positions, which calls for frequent re-optimization due to mobility. This introduces switching in the robot dynamics, making them hybrid. Uncertainty in the communication and physical domains adds extra complexity in ensuring system performance, e.g., network integrity or task completion.

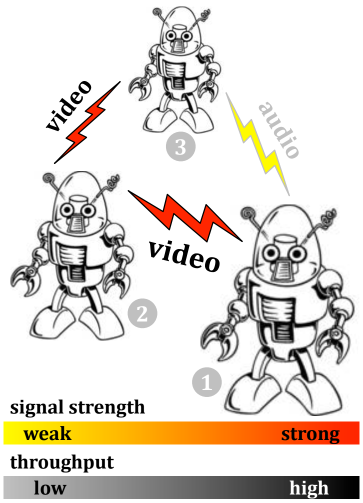

Figure 1: Robot 1 selects different paths to transmit different throughput data to robot 3. Routing can not be captured using graph theoretic techniques.

The goal of this project is to **develop formal methods for networks of mobile robots that integrate control in the communication and physical domains**. This novel technical approach of Integrated Control in the Communication and Physical Domains (ICCPD) offers a number of advantages over other approaches, including:

– more realistic models of robot networks that can be implemented with fewer assumptions,
– lower computational and memory complexity compared to combinatorial graph-based approaches,
– easiness of distributed implementation via distributed optimization of the communication variables (as opposed to optimization of the "global" connectivity metrics in the space of graphs),
– possible connections with graphs and their spectral properties, enabling application of this work to multi-robot tasks that rely on the network spectrum.

I have recently obtained some **preliminary results** in applying Integrated Control in the Communication and Physical Domains (ICCPD) [1]. This was done using a centralized hybrid approach, where the communication variables are the switching signal in the continuous robot controllers. Communication integrity was guaranteed. Additionally, I have devoted a big part of my recent work to **graph theoretic approaches** for topology control of mobile robot networks [2–6]. This work, provides the necessary experience and techniques, such as hybrid systems theory and distributed optimization, to address the challenges of transitioning to communication networks.

There are a number of substantial challenges that need to be overcome in order for the ICCPD theory to show its full potential. These are formulated as **research objectives of this proposal**:

- **Objective 1:** Develop *distributed solution techniques* that integrate control in the communication and physical domains. Robustness to uncertainty, optimality and performance are issues that will be addressed. We will also focus on safe and deadlock-free operation.
- **Objective 2:** Incorporate *richer models of communications* in the control space. Examples include power control, rate adaptation, fading effects, priority flows, etc. We will study how these additional degrees of freedom alter the robot mobility decisions.
- **Objective 3:** Incorporate in our solutions *richer models of the physical domain.* We will introduce complex environments and robot dynamics (as opposed to kinematic point-masses in free space) and study how they affect the interplay between mobility and communications.
- **Objective 4:** Establish *connections with graphs and their spectral properties.* This will allow extending this work to a wide range of robotic applications that involve algorithms that depend on the network spectrum, such as multi-robot rendezvous, flocking and formation control. This objective also ensures the broader impacts of the proposed research.
- **Objective 5:** Apply the results from the previous objectives to *real problems.* This objective involves implementation of various robot tasks and application in other fields including biomolecular, power, and social networks. It will also foster the application of the results both in education and industry, and will ensure the broader impacts of this research.[1]

As an integral part to this research program, we also propose an **educational agenda involving K-12, undergraduate and graduate level education.** The objective of the educational program is to engage students and K-12 science educators in a **multidisciplinary research and learning environment.** As much of the recent progress in science and engineering is spurred by cross-disciplinary efforts and new emerging fields, I believe that it is imperative to educate the next generation of engineers and scientists with this mindset.

At the K-12 level, my group (via the GK-12 program at Stevens) and I will coordinate with the Center for Innovation of Engineering & Science Education at Stevens to develop an outreach program that engages high school teachers, students and underrepresented groups in research oriented activities on campus. I plan to introduce the teachers and students to the potentials and applications of mobile robot networks and the challenges of integrating with communications.

At the undergraduate and graduate levels, I plan to modify an existing introductory course in *Robotics* to include material from this project, and design a new course in *Distributed Control of Networked Robots and Systems*, respectively. Both courses will target multidisciplinary undergraduate and graduate students. Additionally, I will collaborate with the Office of Academic Entrepreneurship at Stevens to encourage research and innovation at the undergraduate level. In both initiatives, I will infuse topics from this project.

I will also pursue **synergistic collaborations with international institutions** in Europe to promote cross-disciplinary research over an international network of young scientists and engineers.

C.2 Technical Approach

Consider a network composed of J robots and a fixed infrastructure with K access points (APs). The robots move in an area of interest to accomplish an assigned task, for which reliable communications with the infrastructure are required. Due to, e.g., power constraints or adverse propagation environments, robots collaborate to maintain a multi-hop network with the APs.

Let $\mathbf{x}_j$ for $j = 1, \dots, J$ denote the position of the robots and $\mathbf{x}_j$ for $j = J+1, \dots, J+K$ the position of the APs. We model communication by a link reliability metric $R(\mathbf{x}, \mathbf{y})$ denoting the

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[1] [redacted]

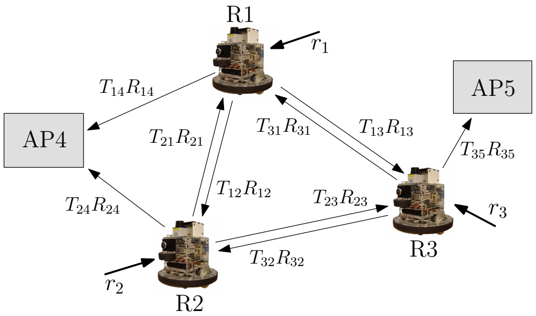


Figure 2: Robotic network consisting of two access points (AP) and three robots (R). Shown are the packet rates r_i generated by every robot as well as the rates $T_{ij}R(\mathbf{x}_i, \mathbf{x}_j)$ sent from robot i and successfully decoded by robot j.

probability that a packet transmitted from a terminal located at position $\mathbf{x}$ is correctly decoded by a terminal at position $\mathbf{y}$ [7]. This function determines the probability $R_{ij} \triangleq R(\mathbf{x}_i, \mathbf{x}_j)$ with which a packet transmitted by node i is correctly decoded by node j. Node j is a robot if $j \leq J$ or an AP otherwise. Furthermore, we denote by r_i the average rate of information, i.e., packets per unit of time, acquired by every robot i. If robot i can reach some of the APs, which is possible if the probability $R(\mathbf{x}_i, \mathbf{x}_j)$ is reasonably large for some $j \in \{J+1, \ldots, J+K\}$, packets are directly conveyed to the corresponding AP. Otherwise, packets are routed to another robot for subsequent transmission. In general, we model this process through the introduction of routing probabilities T_{ij} denoting the probability with which robot i selects node j, either a robot or an AP, as a destination of its transmitted packets. The proposed model is shown in Fig. 2.

Between the time of their generation or arrival from another robot and the time of their transmission packets are stored in a queue, as shown in Fig. 3. A packet leaves the queue at robot i when it is transmitted to any other node j and is successfully decoded by this intended next-hop. Since these two events are independent, the rate at which packets are sent from robot i to node j is $T_{ij}R(\mathbf{x}_i, \mathbf{x}_j)$. Thus, the aggregate rate at which packets leave the ith queue is

$$r_i^{\text{out}} \triangleq \sum\nolimits_{j=1}^{J+K} T_{ij}R(\mathbf{x}_i, \mathbf{x}_j). \tag{1}$$

Similarly, a packet enters the queue at robot i coming from robot j, when robot j selects i as the next hop and i correctly decodes the packet. This happens with probability $T_{ji}R(\mathbf{x}_j, \mathbf{x}_i)$. Since packets are also locally generated at a rate r_i, the rate at which packets arrive at the ith queue is

$$r_i^{\text{in}} \triangleq r_i + \sum\nolimits_{j=1}^{J} T_{ji}R(\mathbf{x}_j, \mathbf{x}_i). \tag{2}$$

Note that the sum in (1) is up to $J+K$ because packets can be sent to another robot or an AP, whereas the sum in (2) is up to J because packets are received from peer robots only (see Fig. 2).

If the average rate at which packets arrive at the ith queue is smaller than the average rate at which packets leave this queue, i.e., if $r_i^{\text{in}} \leq r_i^{\text{out}}$, the number of packets in queue remains bounded with probability one. This provides an almost sure guarantee that packets are eventually delivered to the AP. Therefore, we seek routing probabilities T_{ij} and rates r_i that satisfy the inequality [7–9]

$$r_i + \sum\nolimits_{j=1}^{J} T_{ji}R(\mathbf{x}_j, \mathbf{x}_i) \leq \sum\nolimits_{j=1}^{J+K} T_{ij}R(\mathbf{x}_i, \mathbf{x}_j). \tag{3}$$

Definition 1 (Network integrity) *We define by network integrity the ability of all robots in a network to communicate with the infrastructure at a basal rate of r_{i0} packets per time unit.*

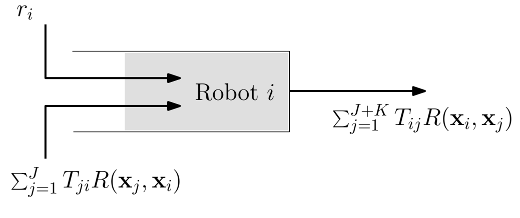


Figure 3: Queue balance equations for robot i.

Ensuring network integrity requires routing probabilities T_{ij} and rates r_i that satisfy (3) and also $r_i \geq r_{i0}$ for all $i \in \{1, \ldots, K\}$. Let $U_i(r_i)$ be a concave utility function (see Remark 1) and define the optimization problem [7–9]

$$P \triangleq \max_{T_{ij}} \left\{ \sum\nolimits_{i=1}^{J} U_i(r_i) \;\; : \;\; r_{i0} + \sum\nolimits_{j=1}^{J} T_{ji}R(\mathbf{x}_j, \mathbf{x}_i) \leq \sum\nolimits_{j=1}^{J+K} T_{ij}R(\mathbf{x}_i, \mathbf{x}_j), \;\; \sum\nolimits_{j=1}^{J} T_{ij} \leq 1 \right\}, \tag{4}$$

where the constraints are required for all $i \in \{1, \ldots, K\}$. For given robot positions $\mathbf{x}_i$, the reliabilities $R(\mathbf{x}_i, \mathbf{x}_j)$ are fixed and the problem in (4) attains a simple convex form. However, this is not the case for mobile robots that move to accomplish their assigned task. In the simplest case, these are described by kinematic point-masses with positions $\mathbf{x}_i$ reacting to control inputs $\mathbf{u}_i$ as

$$\dot{\mathbf{x}}_i = \mathbf{u}_i, \quad i = 1, \ldots, J. \tag{5}$$

Definition 2 (ICCPD) *Integrated Control in the Communication and Physical Domains consists of joint determination of communication and physical variables, e.g., routes* $\{T_{ij}\}_{i,j=1}^{J,J+K}$ *and velocities* $\{\mathbf{u}_i\}_{i=1}^{J}$*, from the system* (4)–(5) *that ensure: (i) desired behavior, e.g., communication rates* r_i *that exceed* r_{i0} *at all times, and (ii) performance, e.g., completion of assigned tasks.*

ICCPD will typically result in **hybrid systems** defined by the composition of discrete-time communication (4) and continuous-time motion (5). Additional performance specifications can be incorporated, increasing applicability of ICCPD, but also its complexity (see Section C.5).

Remark 1 (Utility functions) *The utilities* $U_i(r_i)$ *in* (4) *are metrics used to compare different operating points of the wireless network. Thinking of nodes as economic agents and of utilities* $U_i(r_i)$ *as the value of rate* r_i*, the network's objective is to maximize the social value* $\sum_i U_i(r_i)$*. Utilities employed in practice are typically linear* $U_i(r_i) = w_i r_i$ *or logarithmic* $U_i(r_i) = \log(r_i)$ *[7, 10]. Linear utilities yield larger rates, while logarithmic utilities yield fairer operating points because they penalize small rates* r_i*. Utility functions can be used to implement congestion control, or for power management of the network (see Section C.5.1(OBJ 1.3)).*

C.3 Related Work

Mobile robot networks have recently emerged as an inexpensive and robust way to address a wide variety of tasks ranging from exploration, surveillance and reconnaissance, to cooperative construction and manipulation. Efficient information exchange and coordination between members of the team are critical for successful completion of these tasks. In fact, recent results in distributed consensus have shown that multi-hop communication is necessary for convergence and acceptable performance of the algorithms under consideration [11–18].

Modeling communication in multi-robot systems has typically relied on constructs from graph theory. In particular, proximity graphs have been repeatedly used to capture multi-hop communications, with disc and weight based models gaining the most popularity. This is consistent with early approaches to wireless networking that used disk models to abstract the physical layer [19–24]. In this context, communication becomes equivalent to topological connectivity, defined as the property of a graph to transmit information between all pairs of its nodes.

Graphs have long been used a models of local interactions in the field of mobile robotics. However, their structural properties, such as topological connectivity, did not become a control objective until recently with the work of [25] on connectivity preserving rendezvous. Since then, a large amount of research has been targeted in this direction, and a wide range of applications and solution techniques have been proposed. Approaches can be classified into those that increase network connectivity [3, 26–29] and least restrictive ones that allow links to be lost [2, 4, 30–32]. Alternatively, they can be classified in centralized [2, 3, 26, 32] and distributed [4, 27–30], with the former typically based on semidefinite programming [26, 27, 32] or potential fields [3], and the latter on switched and hybrid systems theory [4, 28, 30]. These results have been successfully used in many multi-robot applications, such as connectivity preserving rendezvous [28], flocking [6] and formation control [28], and also extended to other setups, including noisy communications [33–36].

Although graphs provide a simple and clean abstraction of inter-robot communications, it has long being recognized that since links in a wireless network do not entail tangible connections, associating links with arcs on a graph can be somewhat arbitrary [37]. Indeed, topological definitions of connectivity start by setting target signal strengths to draw the corresponding graph. Even small differences in target strengths might result in dramatic differences in network topology [38]. As a result, graph connectivity is necessary but nearly sufficient to guarantee communication integrity, which translates to the ability of a network to support desired communication rates.

A simple, yet effective, modification is to use graph models that associate weights to links used to capture either the signal strength [39], or the packet error probability of the link [40, 41]. When using reliabilities as link metrics it is possible to model routing and scheduling problems as optimization problems that accept link reliabilities as inputs [42, 43]. The key idea proposed in this project is to define connectivity in terms of communication rates using optimization formulations that describe operating points of wireless networks in terms of optimality criteria.

The use of optimization as a mathematical tool to analyze network protocols dates back to [44] and [45] and has been extensively used in wired [46–48] and wireless networks [7–10, 49]. General optimal wireless networking problems are defined to determine end-to-end user rates, routes, link capacities, and transmitted power, as well as frequency and power allocations [50–54]. While in general this leads to problems with substantial computational complexity, recent results have shown that significant simplifications can be afforded by working in the dual domain [55]. The intellectual merit of the research proposed here stems from the **use of optimal wireless network design to develop novel alternatives for mobility control**.

C.4 Research Contributions and Preliminary Results

C.4.1 ICCPD for maintenance of network integrity

As a first step to ICCPD, we have developed a *centralized hybrid control scheme consisting of continuous-time motion controllers* (5) *composed with periodic re-optimization of the routing probabilities* T_{ij} (4), which is necessary due to robot mobility [1]. The routing variables are the switching signal in the motion controllers, which depend on artificial potential functions $\phi_i : \mathbb{R}^{dJ} \to \mathbb{R}_+$ with $\phi_i \triangleq \phi_{i,b} + \phi_{i,c} + \phi_{i,t}$ and $d > 0$ the workspace dimension. These are composed of a *barrier potential*

$$\phi_{i,b} \triangleq \left[\left(\sum\nolimits_{j=1}^{J+K} T_{ij}R_{ij}\right)^2 - \left(\sum\nolimits_{j=1}^{J} T_{ji}R_{ji} + r_{i0}\right)^2\right]^{-1} \tag{6}$$

ensuring internal consistency of the routing variables T_{ij} at terminal i (cf. queue balance constraints in problem (4)), a *collision avoidance potential* of the form $\phi_{i,c} \triangleq \sum_{j\neq i} \|\mathbf{x}_i - \mathbf{x}_j\|_2^{-2}$, and *task potentials* $\phi_{i,t}$ that can be designed to model a variety of tasks, as it will be discussed bellow. Under mild conditions on the functions $R(\mathbf{x}_i, \mathbf{x}_j)$ and $\phi_{i,t}$, we can define a closed loop hybrid system by the integration of the discrete optimization (4) with the resulting motion controllers

$$\dot{\mathbf{x}}_i = -\nabla_{\mathbf{x}_i}\phi_i, \quad \text{for all } i = 1, \ldots, J. \tag{7}$$

Proposition C.1 (Network Integrity [1]) *The closed loop system* (4) – (7) *guarantees that all robots can communicate with the infrastructure at a basal rate of* r_{i0} *packets per unit time. Moreover, the robot velocities are bounded and collisions between robots are avoided.*

For example, consider simple models of channel reliabilities that are deterministic, decreasing functions of the inter-robot distances $\|\mathbf{x}_{ij}\|_2 \triangleq \|\mathbf{x}_i - \mathbf{x}_j\|_2$. One possible choice is [1]

$$R_{ij} \triangleq \begin{cases} a\|\mathbf{x}_{ij}\|_2^3 + b\|\mathbf{x}_{ij}\|_2^2 + c\|\mathbf{x}_{ij}\|_2 + d, & \text{if } l \leq \mathbf{x}_{ij} \leq u \\ 0, & \text{otherwise} \end{cases},$$

with $0 < l < u$ lower and upper bounds on the inter-robot distances, respectively, and the constants a, b, c and d closen such that $R_{ij} = R(\mathbf{x}_i, \mathbf{x}_j)$ is a twice differentiable function ranging from 0 to 1 (Fig. 4). This is a polynomial fitting of experimental curves found in the literature, e.g., [56].

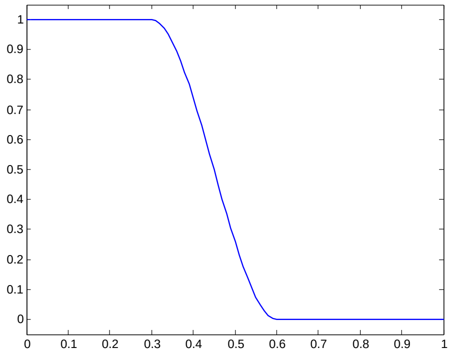
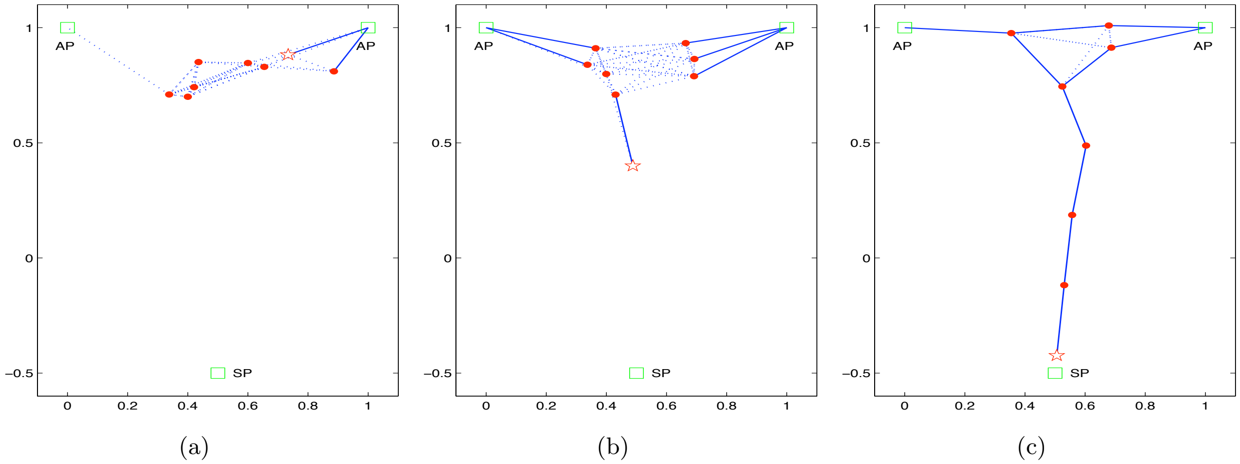


Figure 4: Channel reliability $R(\mathbf{x}_i, \mathbf{x}_j)$ for $l = .3$ and $u = .6$ and the scenario illustrated in Fig. 5.

Suppose that a mobile robot network consisting of $J = 8$ robots is deployed to establish communication between $K = 2$ access points (APs) and one service point (SPs) in $\mathbb{R}^2$ (Fig. 5). One robot is the *leader* that is responsible for serving the SP and the other robots relay the information back to the APs. We choose $\phi_{i,t} \triangleq \frac{1}{2}\|\mathbf{x}_i - \mathbf{x}_{i,t}\|_2^2$ and $r_{i0} \triangleq .8$ for the leader, and $\phi_{i,t} \triangleq 0$ and $r_{i0} \triangleq 0$ for all relay robots, where $\mathbf{x}_{i,t}$ denotes the location of the service point. This formulation is consistent with the classification of robots into relay robots and leaders, since leaders collect measurements and generate data, while relay robots relay this information back to the access points. In this scenario, the utilities $U_i(r_i) \triangleq 0$ for all robots. Shown in Fig. 5 is the evolution of the system under the influence of the leader.



(a) (b) (c)

Figure 5: Establishing reliable communications between access and service points. Communication links are solid or dashed depending on their quality $T_{ij}R_{ij}$, with solid ones indicating higher quality. Packets flow towards the APs.

Remark 2 (Task completion) *For simplicity, we have considered task completion as a secondary objective, subsidiary to communication integrity. While this implies that robots may not be able to complete their tasks, it is consistent with the idea that basal rates* r_{i0} *are critical for task completion. Ensuring task completion raises fundamental questions in controller design (see Section C.5.1).*

Remark 3 (The take-home message) *The simple scenario described in this section (see also [1]) highlights the potential of ICCPD when applied to more complicated problems. For example, compare the linear formulation of* (4) *with the semidefinite one of similar centralized graph theoretic approaches [26]. With ICCPD, control is performed directly in the configuration space. However, in [26], optimal graphs need to be embedded in the configuration space, which is a challenging task.*

C.4.2 Integrated control in the graph and physical domains

Existing results by the PI and other researchers in the area of mobile robot networks have employed **graph theory** to capture the communication space. The property of interest in this case is network connectivity, which holds true if there exists a sequence of links, i.e., a path, between every pair of nodes in the graph. The appealing aspect of this formulation is that there are equivalent algebraic representations of graphs, in terms of matrices and their spectral properties [57], that can be used in combination with motion control to maintain connectivity of mobile communication networks.

Approaches that **integrate control in the graph and physical domains** exploit a variety of tools, including optimization [26,27], continuous systems [3] and hybrid systems [4,30]. Recently, distributed solutions [4, 27, 30] have been shown to be **highly successful, yet computationally expensive**, in controlling the topology of mobile networks, for various cases, including flocking [6], rendezvous [58] and formation control [28], as well as experimentally [59]. This work by the PI and other researchers provides the necessary experience and techniques, such as hybrid systems theory and distributed optimization, to develop the theory of ICCPD and address the challenges of transitioning from graphs to communication networks.

C.5 Proposed Research

The objectives of the proposed research, as stated in the introduction, can be summarized as developing new models, theoretical results and algorithms to accurately address a wide range of applications involving mobile robot networks. The relations between these objectives are illustrated in Fig. 6. The research program spans a broad spectrum of theoretical and applied research, and it embodies a career development plan with short and long term goals.

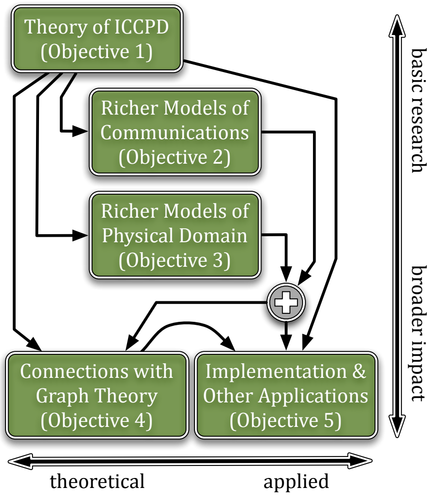


Figure 6: Block diagram of the relations between the research objectives.

C.5.1 Objective 1: Developing the theory of ICCPD

There are several research directions in developing the theory of integrated control in the communication and physical domains (ICCPD) that can further enhance its applicability. These directions are listed and explained below, in the order of priority/execution order, i.e. the ones that are mentioned earlier have more supporting preliminary results.

OBJ 1.1: Distributed algorithms. In the technical description in Section C.2 we assumed that routes and controls are computed at a central location. This entails a large communication cost to collect information about the network topology and communicate routes and control actions to the robots. It also incurs significant delays and is vulnerable to failures. This research objective aims to overcome these limitations by developing distributed ICCPD techniques.

A potential powerful set of tools we will explore is *distributed optimization and dual decomposition.* For the problem under consideration, the Lagrangian

$$\mathcal{L}(\boldsymbol{\lambda},\mathbf{T}) = \sum\nolimits_{i=1}^{J} U_i(r_i) + \lambda_i \left[\sum\nolimits_{j=1}^{J+K} T_{ij}R(\mathbf{x}_i,\mathbf{x}_j) - T_{ji}R(\mathbf{x}_j,\mathbf{x}_i)\right]$$

can be written as a sum of local Lagrangians $\mathcal{L}_i(\boldsymbol{\lambda},\mathbf{T}) = U_i(r_i) + \sum_{j=1}^{J+K} T_{ij}R(\mathbf{x}_i,\mathbf{x}_j)\big(\lambda_i - \lambda_j\big)$ that depend only on the variables $\{T_{ij}(\boldsymbol{\lambda})\}_{j=1}^{J+K}$ associated with terminal i. This allows for the use of distributed subgradient algorithms to maximize the local and, therefore, global Lagrangian. The key research issue to be addressed here is the *integration of distributed optimal communication with distributed control in the physical domain.* This involves the following considerations:

(i) The iterates $\{T_{ij}(t)\}_{j=1}^{J+K}$ obtained by distributed subgradient algorithms are not exact solutions of (4) for all time, which precludes verbatim use of potentials as in (6). On the other hand, speeding up the iterations or reducing the robot velocities is not desirable. Since the dual variables $\lambda(t)$ provide information about the amount of constraint violation, we will investigate the use of potentials in the dual domain as an alternative to potentials in the primal domain.

(ii) Convergence of subgradient iterations holds for static environments [60], i.e., when $R(\mathbf{x}_i, \mathbf{x}_j)$ is fixed. In dynamic environments, it is reasonable to expect that the variables $\{T_{ij}(t)\}_{j=1}^{J+K}$ will converge to a point with suboptimal yield. The gap between achieved and optimal yields is likely to depend on the relative values of the convergence rate of communication and the robot velocities.

(iii) The dual decomposition subgradient iteration is a possible approach to obtain a distributed implementation, but other alternatives exist, e.g., [61]. These alternative decompositions will also be investigated. Our goal is to determine their respective merits in terms of integration with physical dynamics and suboptimality gap in continuously varying setups.

OBJ 1.2: Robust and stochastic algorithms. Signal strength is typically subject to random variations, i.e., fading, which makes communication unpredictable. So are robot localization or distance measuring systems. This introduces extra randomness in any reliability model that involves inter-robot distances, especially in the absence of line-of-sight, as is the case in indoor environments.

As a first step, we will consider channel reliabilities $R(\mathbf{x}_i, \mathbf{x}_j)$ with given higher order statistics, i.e., mean and covariance, and impose probability bounds on the integrity constraints (4), i.e.,

$$\mathbb{P}\left\{r_{i0} + \sum\nolimits_{j=1}^{J} T_{ji}R(\mathbf{x}_j, \mathbf{x}_i) \leq \sum\nolimits_{j=1}^{J+K} T_{ij}R(\mathbf{x}_i, \mathbf{x}_j)\right\} \geq \eta, \quad \text{for all } i = 1, \ldots, J.$$

Under Gaussian noise assumptions, this constraint can be expressed as a second-order cone constraint (SOCC) [62]. Since the variables in SOCC are typically tightly coupled by the induced norm and higher order statistics (as opposed to OBJ 1.1), a great challenge is the *distributed implementation of these robust formulations.* Supporting preliminary results based on linear approximations of the nonlinear constraints [63] indicate that distribution is possible, although at the cost of complexity and robustness. Other noise models, e.g., uniform, will also be explored.

Another useful class of approaches are stochastic algorithms that capture uncertainties about the future via the introduction of probability distributions in the space of possible future realizations. Such have been recently explored for navigation and communications in [64] and [65], respectively. Since wireless channels depend on robot positions, a fundamental challenge that we will address is the *statistical correlation between the physical and communication variables* with the goal to extend our results to stochastic environments.

OBJ 1.3: Optimal control algorithms. An important specification in the design and deployment of mobile robot networks is the lifetime of the network. This can critically affect task completion and, therefore, can become a deciding factor in the adoption of such systems. Therefore, algorithms that ensure task completion in minimum time are clearly the most desirable ones.

Network lifetime is closely related to power consumption. This depends on both on mobility and communication [66–68]. A possible powerful tool to address this challenge is *decentralized model predictive control (DMPC)*, that can be used to minimize the total power consumption of the network over finite or infinite time horizons. DMPC is flexible in handling many and possibly conflicting optimization objectives and control constraints [69–71]. We will first use simple models of power consumption, e.g., see [72], and then move towards more complicated ones (see OBJs 2.1, 2.2 and 3.1). The great challenge with DMPC, and MPC in general, is ensuring stability. For this, we will explore the use of contractive constraints in the optimization problem [73, 74].

OBJ 1.4: Ensuring performance guarantees. This research thrust is closely related to OBJs 1.1, 1.2 and 1.3. Different definitions can be given to the notion of "algorithm performance". In this project, we focus on the following three.

(i) *Tractable, fast and scalable:* We will emphasize on convergence speed and amount of message passing. Recent research in the closely related area of graph theoretic connectivity control (see Section C.4.2), has shown that these metrics are inversely proportional to the amount of distribution and conservativeness of the solutions. Additionally, complexity may also arise from inefficient integration of interacting algorithms, e.g., see OBJ 1.1. Different integration schemes will be explored and distribution vs. performance tradeoffs will be characterized.

(ii) *Safe operation:* In this project, safe operation typically includes components, such as communication integrity, collision avoidance and obstacle avoidance. Safe operation can be either ensured deterministically or with high probability. These are addressed in OBJs 1.1 and 1.2.

(iii) *Deadlock-free operation:* A deadlock typically refers to the inability of a system to complete its task. In terms of dynamical systems, it is equivalent to entrapment in local minima. Deadlocks typically appear when conflicting objectives are present in the control. Such can be network integrity/connectivity vs. "spreading", or navigation vs. collision avoidance. Tasks, such as rendezvous and flocking, are not challenged by limited communication ranges and, therefore, can be achieved by deadlock-free algorithms [6, 28]. However, formation control and similar applications pose significant challenges in this respect. To date, most approaches are either restricted to local convergence results, or assign secondary priority to task completion [4].

– We will explore the extra degree of freedom that routing provides in defining a *cyber* communication network over the proximity-based topological one. By controlling this network we will be able to bypass communication constraints that restrict robot motion.

– We will explore ways to involve distant robots, that are idle in terms of participating in the task, in the resolution of deadlocks. Efficient communication will be critical to reach these robots.

– We will explore periodic communication schemes to allow the robots perform their assigned tasks in-between communication rounds. We will build upon recent results by the PI [75] and others [76].

– For homogeneous robots with same capabilities, assignment of specific tasks to the robots is irrelevant. We will explore task re-assignment to resolve deadlocks due to collision or communication constraints. For this, we will use and extend recent work by the PI including [77–79]. We expect re-assignment to be a potentially very powerful tool in the design of deadlock-free algorithms.

C.5.2 Objective 2: Introducing richer models of the communication space

In order to apply the control algorithms that we propose to develop, we need to extend our solutions to richer and more accurate communication models. These are listed and explained bellow.

OBJ 2.1: Power control and rate adaptation. The function $R(\mathbf{x}_i, \mathbf{x}_j)$ captures the inherent unreliability of wireless links. However, $R(\mathbf{x}_i, \mathbf{x}_j)$ is not fixed as it depends on communication rates and transmitted power. Depending on the technique used for multiple access this modification might alter the fundamental properties of (4), leading, for example, to non-convex formulations for optimal communication. In these cases, convex relaxations will be pursued. Additionally, the incorporation of power into the control objective leads to control tradeoffs, including:

(i) *Power regulation over time:* We will address scenarios where the autonomous system needs to pass through intermediate configurations where communication integrity is maintained at the cost of substantial power consumption as long as this is compensated by reduced power consumption at steady state. We will study how this affects network lifetime and task completion (see OBJ 1.3).

(ii) *Power for mobility vs. communication:* In order to satisfy a constraint it is possible to let robots move for that purpose, increase transmitted power, or a combination of both. Our goal is to find the action that satisfies the constraint with minimum power expenditure (see OBJ 1.3).

OBJ 2.2: Fading effects. A defining characteristic of wireless communications is the presence of fading, i.e., random variations in link quality. The technical approach of Section C.2 captures fading in the reliabilities $R(\mathbf{x}_i, \mathbf{x}_j)$ (see Fig. 4), however, it is also natural to consider adaptation of power and rates to observed fading states. We will introduce a link capacity function $C(\mathbf{x}_i, \mathbf{x}_j, \mathbf{h}, P_i(\mathbf{h}))$ that depends on robots' positions $\mathbf{x}_i$, fading $\mathbf{h}$, and transmitted power as a function of fading $P_i(\mathbf{h})$. While incorporation of fading usually leads to computationally intractable formulations, recent results suggest alternatives to significantly reduce the computational expense [55]. We will leverage these results to incorporate fading in mobility control, at manageable computational cost.

OBJ 2.3: General communication setups. Besides communication towards the fixed infrastructure, we will consider communication from the infrastructure, as well as communication between agents. These different exchanges will coexist in the network and have varying requirements in terms of required rates, priorities and delay. Their development is critical for most multi-robots applications that rely on communication between all pairs of nodes, e.g., consensus algorithms.

We will model such situations using *multiple flows* so that the rates $r_i = r_i^k$ and the routing variables $T_{ij} = T_{ij}^k$ are indexed by a flow index k. This will result in separate rate constraints (3) for each flow, and routing constraints $\sum_j T_{ij} \leq 1$ being replaced by $\sum_k \sum_j T_{ij}^k \leq 1$. While neither of these modifications alters the fundamental properties of optimal communication (4), they raise important considerations regarding *flow prioritization* and its effect on mobility decisions. For this, we will employ families of barrier functions in the primal and dual domains (see OBJ 1.1).

C.5.3 Objective 3: Introducing richer models of the physical domain

We will introduce richer sets of physical constraints that more accurately capture the environments and robot dynamics. Objectives 2 and 3 are related since, e.g., complex environments introduce interference which requires richer models of communication.

OBJ 3.1: Effect of complex environments on communications. In indoor operation, refraction, reflection and diffraction of electromagnetic waves in walls and obstacles creates an interference environment in which the euclidean distance between robots is an insufficient metric to capture channel rates; as in Fig. 4.

As a first approximation we will employ *abstractions of interference* that depend solely on the environment's structure. The key idea is to replace the euclidean distances in the models for the reliabilities (see Fig. 4) by geodesic distances. This abstraction captures the observation of weaker communications in more cluttered areas of the environment; see Fig. 7. The geodesic distance model will be further enhanced with more accurate models of indoor communications, that will account for the effects of interference and also incorporate *signal reflection and absorption*. While these models will be made as accurate as possible, they will fail to capture some second order effects. This motivates *online estimation of link capacities* that will be pursued through the construction of empirical maps of signal strength [80].

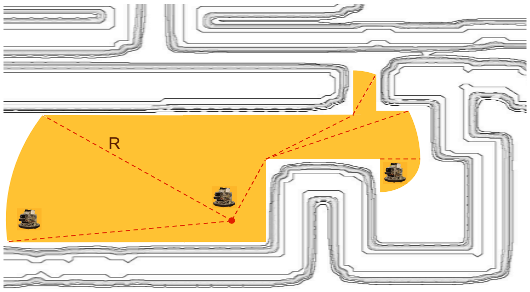


Figure 7: Indoor communication based on geodesic distances. The geodesic distance between two points is the euclidean length of the shortest path on the graph defined on the environment's (reflex) vertices.

OBJ 3.2: Effect of complex environments and robot dynamics on navigation. Navigation in complex non-convex environments requires new control strategies that respect the additional constraints. Approaches based on artificial potentials are no longer efficient, while the complexity of discrete planning grows exponentially with the environment complexity.

As a starting point, we will use a *hybrid scheme* consisting of both artificial potentials and discrete planning for navigation. This will rely on defining a sequence of waypoints on a visibility graph of the environment that continuous motion controllers can incorporate to satisfy distance constraints between the robots, e.g., connectivity and collision avoidance, or track targets; see Fig. 8. This approach "convexifies" the environment, since between consecutive waypoints it is obstacle-free.

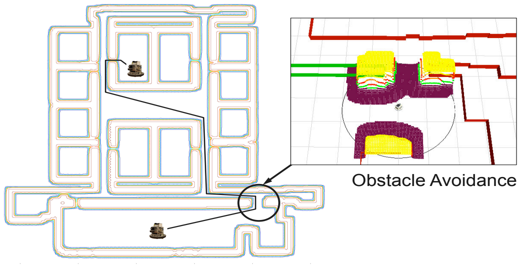


Figure 8: Indoor navigation using geodesic paths. Navigation along edges of geodesic paths "convexifies" free space.

We will enhance these results with *complex dynamics*, due to differential drive robots for indoor applications, or robots with high maneuvering capabilities for aerial applications, e.g., quad-rotors [81]. Maintaing such vehicles within communication range is a challenging task. Recent literature mainly focuses on hovering or conservative navigation [82, 83]. Robust and stochastic algorithms will be useful in dealing with uncertainty and complexity due to dynamics (see OBJ 1.2).

C.5.4 Objective 4: Establishing connections with graphs and their spectral properties

The convergence speed of *consensus* [18,84] and the mixing rate of *Markov chains* [85] depend on the second smallest and second largest (in absolute value) eigenvalue of the network, respectively. Since most multi-robot applications, such as rendezvous [86, 87], flocking [88] or formation stabilization [89, 90], rely on some form of these algorithms, this objective focuses on controlling the spectral properties of communication networks and extending the results to applications.

OBJ 4.1: Spectral control of communication networks. Communication networks are weighted, directed graphs with edge weights equal to the transmission rates $T_{ij}R(\mathbf{x}_i, \mathbf{x}_j)$. Therefore, it is straightforward to define their spectrum [57,91]. The key idea that motivates this research (and also plan of attack) is that the spectral properties of communication networks can be controlled by an **eigenvalue utility function**, as in Section C.2. Indeed, maximization of the algebraic connectivity is a concave problem that can also be solved in a distributed way [27]. Similarly, recent work by the PI has shown that the eigenvalue statistics can be computed in a distributed way using consensus [92]. This framework calls for relating operating points that are optimal for communications or (spectral) applications. The example of high connectivity (desirable for fast consensus) associated with congestion (undesirable for communications), indicates that these utilities might be conflicting. We will explore these tradeoffs and integrate spectral design with ICCPD. Since the spectrum is a global graph quantity, this is a challenging task (see Objective 1).

OBJ 4.2: Mobile robot network applications revisited. We will revisit multi-robot applications in the context of communication networks with desired spectral properties, for given applications (see OBJ 4.1). A major challenge is the development of deadlock-free algorithms (see OBJ 1.4). This objective ensures the broader impact of this work.

C.5.5 Objective 5: Implementation and other applications

This objective involves *theoretical results* that extend this research to specific applications, as well as *implementation* in the form of software tools and experimentation. Successful completion of this thrust will enhance the broader impacts of the research program and ensure the relevance of the effort towards the other objectives.

OBJ 5.1: Experimentation with multi-robot platforms. We will undertake experiments to validate theoretical findings and inform unforeseen research challenges. Differences between models and real-world conditions may be significant due to, e.g., hidden complexities in the electromagnetic propagation environment, or effects of distributed asynchronous control, sensing, and actuation.

Our robotics laboratory is currently under development and will be completed during the course of this project. It will involve an indoor free space that is approximately 5×7m in dimension, which will be equipped with 6 overhead Point Grey Dragonfly2 cameras for localization. Initially, the proposed experimental testbed will consist of approximately 10 *iRobot Roomba* robots with on-board URG lasers and a dedicated 802.11a wireless network for communication. Future plans involve experimentation with *quadrotors*, as they possess complex dynamics (see OBJ 3.2). Following the line of the PI's previous work [59], implementation will be in C++ using the Player/Stage/Gazebo project, since it allows for accurate models of the robots for use in simulation. Experiments will also be performed in collaboration with Dr. [redacted] (see attached Letter of Collaboration). Dr. [redacted] and his group have been developing expensive and sophisticated multi-robot platforms that can challenge the performance of our algorithms. This collaboration started in the spring 2010 and has led to one proposal submitted to [redacted].

This objective will also be coupled with the *educational and outreach program* by integrating experimentation in the learning cycle [93,94]. We will apply such learning models to undergraduate and K-12 education to familiarize students with mobile robotics and the interplay with communications (see attached Letter of Collaboration).

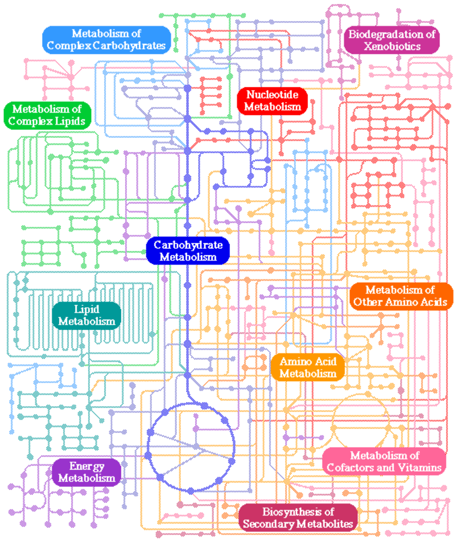


Figure 9: Metabolic network.

OBJ 5.2: Application to biomolecular networks. Gene regulatory networks capture the interactions between genes and other cell substances, resulting from the fundamental biological process of transcription and translation. The product of this process is enzymes that facilitate various biochemical reactions in the cell, that form its metabolic network; see Fig. 9. Analysis of metabolic networks is crucial in drug discovery where it can be used in the identification and knockout of targeted pathways [95]. This process is particularly difficult due to the size of these networks but also due to their high degree of robustness to single reaction knockouts [96–99].

Although biological networks do not have the same dynamic nature that communication networks have due to mobility, they have a strong routing component, called *metabolic flux*, which depends on flux balance equations (relate with (3)) and high uncertainty. We will contribute by: (i) determining *flux distributions* in metabolic networks, (ii) studying flux response to *reaction knockdowns*, (iii), introducing *uncertainty* in capacity constraints, cell growth models and enzyme kinetics, (iv) developing *distributed solutions* for parallel computation, and (v) developing *software tools* that implement the proposed algorithms. These results will complement existing literature, as *elementary flux modes* and *extreme pathway analysis* [100, 101], especially in addressing parameter uncertainty [102, 103]. This method is appealing due to its ability to jointly model topological constraints and routing, and the iterative nature of the proposed algorithms that allow for fast re-optimization and parallel implementation. *Distributed and robust identification* of gene regulatory networks will also be pursued. We will build upon recent results by the PI [104, 105].

This effort will be coupled with the *educational and outreach program* via the software tool that will disseminate the research outcome to the industry and academia. It will be initially developed in MATLAB and will consist of core computation algorithms, format conversion, and graphical user interface, and will involve graduate, undergraduate and select high school students, respectively.

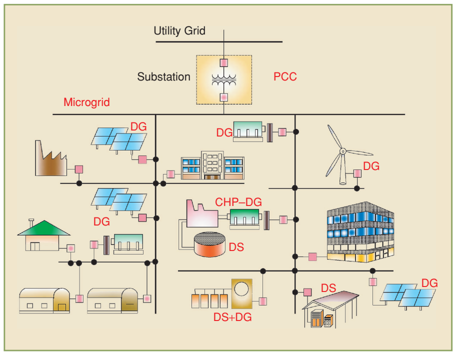


Figure 10: Microgrid connected to grid.

OBJ 5.3: Application to smart energy networks. Smart grids and micro-grids offer (i) an efficient energy delivery and supply system based on co-located distributed energy resources and loads, (ii) a secure and reliable power supply configuration with service differentiations based on customer technology preference and power quality desires, and (iii) an energy delivery structure that can operate independent from the main grid during power outages or an energy crisis [106–110]. Their application poses significant challenges related to voltage, frequency, power and flow regulation, but also economical challenges related to energy pricing.

The PI will pursue this research direction in full support of the Office of Academic Entrepreneurship (OAE) at Stevens (see attached Letter of Collaboration). Smart energy networks are a perfect fit for the framework proposed here. Energy pricing gives a dynamic nature to the network and affects user decisions and, therefore, energy flow, network stability etc. We will emphasize on distributed, reliable, and provably correct algorithms for *energy routing* subject to pricing and grid operation. For this we will leverage recent results on micro-grid control [111–117].

OBJ 5.4: Other potential applications. The theory of ICCPD has a wide applicability, which will be further enhanced by the results of the previous objectives of this program. In the long term, we will continue to seek relevant applications for this technique. The opportunities abound, since many engineering systems, e.g., automated road networks, or natural systems, e.g., social networks, possess a similar network structure and face similar challenges.

C.5.6 Timeline and milestones

The timetable for the proposed research program is shown in Fig. 11, and can be broken down as follows.

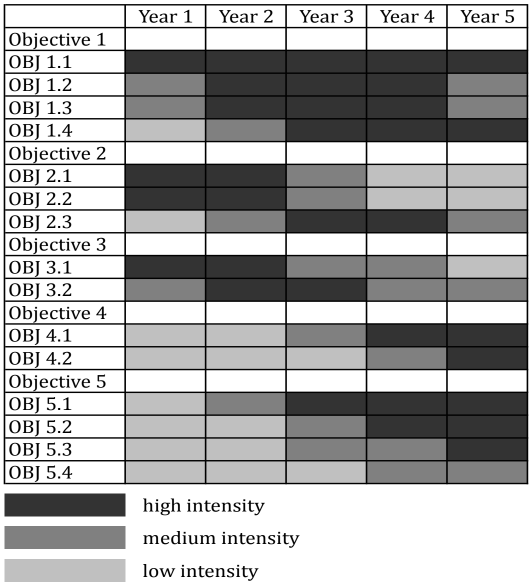
Year 1. The effort will be concentrated in parts of Objectives 1, 2 and 3. We will focus on developing distributed algorithms for ICCPD, and explore the effects of power control, fading and complex environments.

Year 2. We will continue the effort from the previous year and build on the results. We will also introduce uncertainty and robot dynamics in our models, and begin setting up preliminary experiments.

Year 3. We will focus on robot dynamics and more general communication setups involving priority flows and different type users. We will integrate these models in our algorithms and emphasize on performance. We will also focus on implementation.

Year 4. The effort in theory and algorithm development will be in integrating the feedback from experimentation. We will explore connections with graph theory as well as applications in robotics and other fields.

Year 5. The theory and algorithm side will continue the effort from previous years. The emphasis will be in integrating our results in applications and disseminating the research output.



	Year 1	Year 2	Year 3	Year 4	Year 5
Objective 1					
OBJ 1.1	█	█	█	█	█
OBJ 1.2	▓	█	█	█	▓
OBJ 1.3	▓	█	█	█	▓
OBJ 1.4	░	▓	█	█	█
Objective 2					
OBJ 2.1	█	█	▓	░	░
OBJ 2.2	█	█	▓	░	░
OBJ 2.3	░	▓	█	█	▓
Objective 3					
OBJ 3.1	█	█	▓	▓	░
OBJ 3.2	▓	█	█	▓	▓
Objective 4					
OBJ 4.1	░	░	▓	█	█
OBJ 4.2	░	░	░	▓	█
Objective 5					
OBJ 5.1	░	▓	█	█	█
OBJ 5.2	░	░	▓	█	█
OBJ 5.3	░	░	▓	▓	█
OBJ 5.4	░	░	░	▓	▓

█ high intensity
▓ medium intensity
░ low intensity

Figure 11: The timetable of the proposed research.

C.6 Broader Impacts & Synergistic Activities

The proposed research is highly relevant for most coordinated tasks performed by teams of mobile robots. Successful completion of this project will provide the necessary theoretical and experimental support in facilitating the design of mobile autonomous systems and fostering their adoption. It will also allow extending these results to other fields facing similar challenges.

The broader impacts of this project are connected to Objectives 4 and 5; see Fig. 12. Spectral design of communication networks will enable a number of multi-robot applications, and will contribute significantly in disseminating the project results in the industry and academia. Also, implementation of this work will contain an educational component, with students being involved in design, innovation and learning, as discussed in the previous section. To meet Objective 5, we have identified several research thrusts, where the algorithms and techniques of this research can have a significant impact. Some are mentioned in the previous section. These directions can be listed and explained as follows.

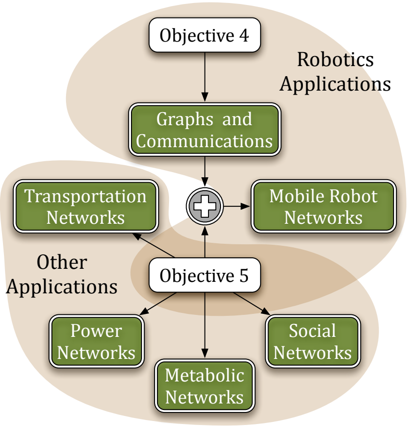


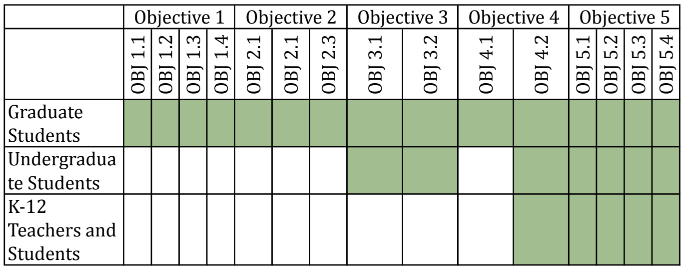
Figure 12: Broader impacts.

- Mobile robot networks: Recent advances in robotics and communications can not be efficiently integrated on real platforms without the necessary theoretical and experimental support. The impact of this research in facilitating the design of mobile autonomous systems and fostering their adoption will be significant. It will provide distributed, robust and scalable algorithms, as well as realistic models that can be applied with fewer assumptions.
- Biomolecular networks: Recent advances in biotechnology have enabled scientists to engineer microorganism cells to perform unnatural functions [118, 119]. In many applications, such as biosynthesis of fuel molecules or drugs, we need to control the behavior of the cells at the molecular level. This is a particularly hard task due to the complexity and uncertainty involved in these systems. We expect our approach to reduce complexity and provide more accurate predictions.
- Smart energy networks: The recent blackout experiences have demonstrated the vulnerability of the electric power system to grid failure caused by natural disasters and unexpected phenomena. Changes in customer needs, additional stress due to liberalized electricity markets, and a high degree of dependency of todays society on sophisticated technological services, intensifies the burden on traditional electric systems and demands for a *more reliable and resilient power delivery infrastructure.* The micro-grid approach is advocated by the US Department of Energy "Modern Grid Strategy" [120, 121] and is currently being extensively studied in many countries including the U.S. (CERTS testbed), Europe ("Microgrids" projects), and Canada (BC Hyrdo "islanding" project) [107]. If successful, the impact of this research in this direction will be tremendous.
- Automated transportation networks: Road networks are dynamic systems that transport passengers between destinations, depending on traffic and its fluctuations. We foresee applicability of the results developed here in problems related to autonomous routing based on traffic estimates.
- Social networks: Social networks are the structures on which processes such as rumor or virus spreading evolve. In these networks, links indicate relations between people, such as friendship, and are subject to possibly changing "reputations". Spreading dynamics depend on the network topology, therefore, information routing in such networks is a possible application of our results.

This project also has an **educational program** that is integrated with the research program, as will be discussed in the following section. The broader impact of the educational program is educating the next generation of engineers and researchers that are fluent in multidisciplinary research collaborations and are aware of the tremendous potentials of such activities. The outreach component of the educational program will also improve the pre-college students' awareness of the potential and attractiveness of research and engineering career.

C.7 Educational Plan

The objective of the educational program is to engage students in a **multidisciplinary research and learning environment.** As much of the recent progress in science and engineering is spurred by cross-disciplinary efforts and new emerging fields, the PI believes that it is imperative to educate the next generation of engineers and scientists with this mindset.



	Objective 1				Objective 2			Objective 3		Objective 4		Objective 5			
	OBJ 1.1	OBJ 1.2	OBJ 1.3	OBJ 1.4	OBJ 2.1	OBJ 2.1	OBJ 2.3	OBJ 3.1	OBJ 3.2	OBJ 4.1	OBJ 4.2	OBJ 5.1	OBJ 5.2	OBJ 5.3	OBJ 5.4
Graduate Students	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Undergraduate Students								🟩	🟩		🟩	🟩	🟩	🟩	🟩
K-12 Teachers and Students											🟩	🟩	🟩	🟩	🟩

Figure 13: Students' involvement in research effort.

The educational program in this proposal is designed to be **integrated**, **parallel**, and have a **mutually beneficial** relationship with the research program. The research program will contribute to the educational program by infusing research material into new and existing courses, and introducing students and educators to multidisciplinary research. On the other hand, the educational program will contribute to the research program by encouraging student participation in research and course development. The relationship between research and educational program will also be strengthened by leveraging **synergistic collaborations** with in-campus organizations and cross-disciplinary collaborators. The involvement of the students in research effort can be summarized in the table shown in Fig. 13. This program encompasses the K-12, undergraduate, and graduate levels of education.

K-12 Education. The PI will collaborate with the Center for Innovation of Engineering & Science Education (CIESE) at Stevens to develop an outreach program targeting local high school science teachers and students and underrepresented groups (see attached Letter of Collaboration). In this effort, the PI will also involve his research group via the NSF GK-12 program at Stevens (see "Graduate Education" bellow). The goal is to enhance high school science curricula with project based learning modules related to the outcome of this research.

(i) *High school science teachers and students:* The PI will work closely with teachers selected through CIESE to encourage and support integration of science and engineering related material in pre-college curricula. Initially, this effort will be part of the ITEST Scale-Up project that focuses on the development of advanced modules for classroom application of autonomous underwater vehicles and signal detection technologies. This research will be infused in this direction.

(ii) *Underrepresented groups:* Involvement of the PI with the ITEST Scale-Up project will provide piloted material that will be used in after-school outreach programs that CIESE is exploring with several partners, specifically targeted to girls. The exposure to real research and design environments will provide students with an opportunity to make better-informed career choices.

Undergraduate Education. To impact undergraduate education, the PI will infuse research material related to this project in an introduction course on *Robotics*. The students will be exposed to the concept of coordinated control and, through class projects, they will develop a first understanding of the effects and challenges of communications.

The PI will also collaborate with the Office of Academic Entrepreneurship (OAE) at Stevens to provide students with the opportunity to participate in this research project and develop technical skills as well as entrepreneurship contents (see attached Letter of Collaboration). This effort is part of the *Technogenesis Summer Scholars Research Program*, that engages top undergraduate students in research, innovative design, and/or business projects alongside faculty and graduate students, for a period of ten weeks during the summer.

Graduate Education. The PI will develop a new graduate course in *Distributed Control of Networked Robots and Systems.* This interdisciplinary course is expected to expose students to the theoretical results and applications of networked systems, and prepare them to interact with both the control and networking communities. A preliminary short version of this course was offered in the Spring 2009 at the University of Pennsylvania as part of a graduate level course in advanced robotics. Development of this course will continue during this project and will include our most recent results. Students will become actively involved in this research through class projects.

The PI and his group will also participate in the NSF GK-12 program at Stevens, in collaboration with CIESE, to support K-12 education. The NSF GK-12 program provides funding for graduate students in NSF-supported STEM disciplines that are involved in K-12 education. This allows graduate students to improve communication, teaching, collaboration, and team building skills, and prepares them for their future professional and scientific careers.

C.8 International Collaboration Plan

At this level, the PI will collaborate with Dr. [redacted] and Dr. [redacted] (see attached Letter and Memorandum). [redacted] are actively involved in many European Union (EU) projects and have multiple collaborations with other universities in the EU. The goal of this collaboration is to promote cross-disciplinary research over a network of young scientists and engineers spanning the United States and Europe. For this, this collaboration will involve exchange of students and faculty members, joint research projects, and sharing of facilities.