HOMOLOGICAL SENSOR NETWORKS

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Sensors and sense-ability

A sensor is a device which measures a domain or environment and returns a signal from which information may be extracted. Sensors vary in scope, resolution, and ability. The information they return can be a simple as a binary flag, as with a metal detector which beeps to indicate a detection threshold being crossed. A more complex sensor, such as a video camera, can return a signal requiring sophisticated analysis to extract relevant data.

An increasingly common application for sensors is to scan a region for a particular object or substance. For example, one might wish to determine the existence and location of an outbreak of fire in a national forest. Questions of more interest to national security involve detection of radiological or biological hazards, hidden mines and munitions, or specific individuals in a crowd. All of these scenarios pose difficult and challenging integration problems.

Numerous strategies exist, aided by the fact that sensor technology provides an expansive array of available hardware. A fundamental dichotomy exists in the approach to sensing an environment based on the number and complexity of sensors. For a fixed cost (monetary, or, perhaps, 'total complexity'), one can deploy a small number of sophisticated 'global' sensors with high signal complexity and fine sensitivity to error. In contrast, one can deploy a large number of small, coarse, 'local' devices which may have larger tolerance to error. Different strategies are appropriate for different tasks: the human body contains examples of sensor systems with small numbers of complex devices (for sight) as well as vast networks of local sensors (for touch).

Technology promises to push the envelope on both sides of this spectrum, yielding new types of powerful, global sensors, as well as local sensors of surprisingly small size. The relevant question for the mathematician is which types of mathematics will be useful in analyzing sophisticated sensor networks.

It may be that the most exciting possibilities lie in the domain of the small. Swarms of local sensors at micro- or nano- scale have the potential to revolutionize the way that we think about security and surveillance problems. However, this brings with it the difficulty of integration. How does one collect local information and collate it into global environmental data?

From local to global

Fortunately, mathematicians have spent centuries carefully contemplating the local-to-global transition. The very term we use to indicate the collection and collation of local data — *integration* — hearkens to the well-established means of relating local information about a function (pointwise derivatives) with a global quantity (the integral).

A more relevant example for our purposes is to be found in simple ideas about the topology of surfaces. Given a triangulated surface, one can ask about its global features. The Classification Theorem for Surfaces implies that the Euler characteristic suffices to determine the homeomorphism type of the surface. The Euler characteristic is as a simple a computation as one could hope for:

$$\chi(\Sigma) = \#V - \#E + \#F,$$

where the triangulated surface Σ has $\#V$ vertices $\#E$ edges and $\#F$ faces.

The efficacy of the Euler characteristic in this example is a consequence of the restricted nature of surfaces. If one were given a more arbitrary space, then the challenge of characterizing global features of the space becomes a more fundamental problem in algebraic topology. Roughly speaking, algebraic topology provides two ways in which to associate to a given space X a collection of algebraic objects which gauge the global features of X.

The first such set of invariants are the *homotopy groups*, $\pi_k(X)$, for $k = 0, 1, \ldots$, the *fundamental group* $\pi_1(X)$ being very well-known. These

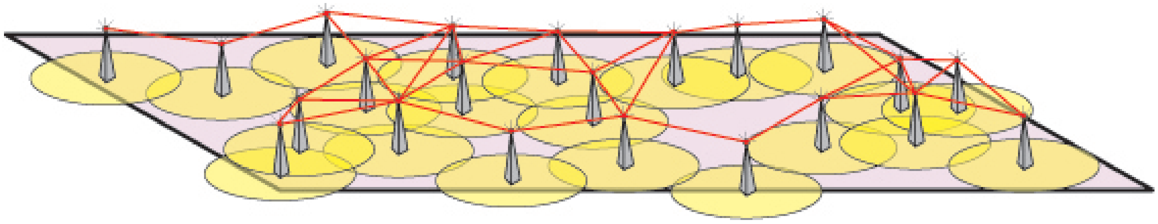

Figure 1: A network of small, local sensors samples an environment at a set of nodes. How can one answer global questions from this network of local data?

groups measure in how many and which ways one can map a k-dimensional sphere S^k into X, two spheres in X being deemed equivalent if they are homotopic relative to some fixed basepoint. Homotopy groups are a very powerful data; however, they are in practice quite difficult to compute. The general computation of homotopy groups of spheres is unknown, and, indeed, is the premier unsolved problem in algebraic topology at this time.

The second set of invariants provide a weaker but more computable option. These are the *homology groups*, $H_k(X)$, for $k = 0, 1, \ldots$. (Properly speaking, homology defers to its algebraic dual — the cohomology groups $H^k(X)$ — as a finer invariant.) Instead of measuring k-spheres in a space up to homotopy, homology measures certain types of *chains*, or objects built from simple oriented pieces (*simplices*). Depending on the type of homology used, these simplices are defined differently, the simplest being in the case of a simplicial complex where the combinatorial simplices from which the space X is built form a basis for simplicial chains. The elements of $H_k(X)$ are *cycles*, or chains with vanishing boundary, and two k-cycles are deemed *homologous* if there is an oriented $(k+1)$-chain which has as its boundary the pair of cycles (with opposite orientation).

Like homotopy groups, the homology groups are an invariant of the homotopy type of the underlying space. This explains why the Euler characteristic χ of a surface is independent of both the triangulation and the homeomorphism type of the surface: χ is the alternating sum of the dimensions of the homology groups.

Unlike homotopy groups, homology groups can be computed via linear algebra. Note: this does not imply that homology can be computed *quickly.* However, recent advances in algorithms for homology (see [11] and references therein) make homology groups a feasible tool for realistic problems.

A simple local network

Motivated by the potential future of sensor-rich environments, we consider a class of simple sensors which can solve global problems based on local communication. For concreteness, we consider the case where nodes lie in a planar polygonal Euclidean domain. Assuming a preference for small-scale devices without GPS or other sophisticated sensors, we eschew a global coordinate system. The topological methods make it possible to work with sensors which are remarkably minimal, having no means of measuring distance, orientation, or otherwise localizing themselves in their environment.

The following assumptions are intended for a sensor network which has two types of capabilities. First, each node can perform some sensing task within a certain radially-symmetric neighborhood. Within this *coverage disk*, the sensor performs its unspecified task, whether it involves video surveillance, detection of radiological or biohazard material, or motion detection. The second capability is node-to-node communication. This is assumed to be very weak: each node broadcasts its unique ID and listens to determine its neighbors.

The one strong assumption we make concerns the boundary of the domain $\mathcal{D}$ in which the nodes lie. We assume for simplicity that the boundary $\partial\mathcal{D}$ is defined by a collection of special *fence nodes* which, though without absolute coordinates, nevertheless possess a sense of "winding" about $\partial\mathcal{D}$. Our precise assumptions are as follows:

A1: Nodes $\mathcal{X}$ broadcast their unique ID numbers. Each node can detect the identity of any node within *broadcast* radius r_b.

A2: Nodes have radially symmetric covering domains of *cover* radius $r_c \geq r_b/\sqrt{3}$.

A3: Nodes $\mathcal{X}$ lie in a compact connected domain $\mathcal{D} \subset \mathbb{R}^2$ whose boundary $\partial\mathcal{D}$ is connected and piecewise-linear with vertices marked *fence nodes* $\mathcal{X}_f$.

A4: Each fence node $v \in \mathcal{X}_f$ knows the identities of its neighbors on $\partial\mathcal{D}$ and these neighbors both lie within distance r_b of v.

To summarize, each node is aware of the identities of those nodes which are within broadcast range r_b. The orientations and distances of these neighboring nodes are unknown. The fence nodes have two additional pieces of data: (1) they know that they are on the boundary of the domain; and (2) each knows the identities of the two neighboring fence nodes.

Apart from the fence nodes (which are used to simplify the statements of theorems), the type of information which this network encodes is very similar to that encoded by a simplicial complex. Local combinatorial data about how elementary pieces are assembled give rise to a global object whose large-scale topological features are of interest.

Simplices for sensors

For such a network, we consider the problem of *blanket coverage*.

> Does the union of the coverage discs about the nodes cover the domain $\mathcal{D}$?

In the context of a surveillance network, the coverage problem is of clear significance. A more benign type of coverage problem vexes anyone with a cell phone in an area of low cell phone tower density. This version of the coverage problem is simpler because the network of cell phone towers is fixed and intentional. The company that built the towers knows exactly where they were built and can compute the union of the coverage discs "by hand" with ease (assuming no hardware failure). Standard algorithms from computational geometry can check for holes quickly, even in cases with many nodes, so long as the node positions are known.

The scenario that we envision differs in that there is no *localization*, or means of determining relative position. This, too, is not an insurmountable difficulty. Indeed, there is an extensive literature on probabilistic methods for coverage problems in networks of randomly distributed points. See, e.g., [12]. Unfortunately, these methods have the very strong restriction of assuming a uniform distribution of points. We would like to solve coverage problems in more realistic settings where one "dumps a bucketful" of sensors in a field, forest, or ocean and then queries the network, perhaps after environmental influences have moved the sensors to unknown positions (except for the fixed fence nodes).

The obvious way to begin is to build the *network graph* of the system. This is a combinatorial graph, Γ, in which vertices correspond to the labeled nodes and (undirected) edges correspond to pairs of nodes which are in mutual broadcast range (within distance r_b). In this graph, the boundary $\partial\mathcal{D}$ is naturally identified with a particular cycle $\mathcal{F} \subset \Gamma$ traversing the fence nodes, thanks to A4. The problem at hand is to determine whether the set $\mathcal{U}$ given by the union of radius r_c balls at $\mathcal{X}$ contains the domain $\mathcal{D}$. The input for this problem is the pair of graphs $(\Gamma, \mathcal{F})$.

Determining the topology of a union of balls is a classical problem, and is easily solved using the notion of a Čech complex (also known as the *nerve*). Given a collection of sets $\mathcal{U} = \{U_\alpha\}$, the *Čech complex* of $\mathcal{U}$, $\mathcal{C}(\mathcal{U})$, is the abstract simplicial complex whose k-simplices correspond to nonempty intersections of $k+1$ distinct elements of $\mathcal{U}$. Thus, the vertices are in bijective correspondence with the cover sets U_α, and edges of $\mathcal{C}(\mathcal{U})$ are in bijective correspondence with nonempty intersections between two cover sets. Higher order intersections generate higher dimensional simplices: see Fig. 2.

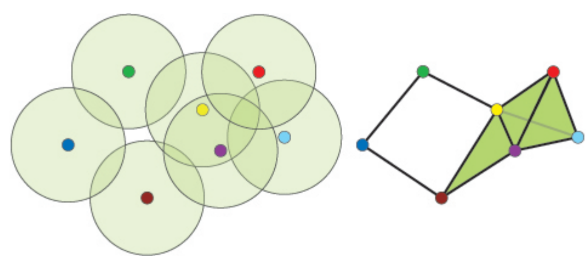

Figure 2: The Čech complex of a cover by convex sets captures the homotopy type of the cover.

Theorem 1 (The Čech Theorem)**.** *If the sets $\{U_\alpha\}$ and all nonempty finite intersections are contractible, then the union $\cup_\alpha U_\alpha$ has the homotopy type of the Čech complex $\mathcal{C}$.*

The equivalence in the Čech theorem is functorial, and in particular there is a relative version which gives us the following result.

Corollary 2. *Under assumptions A1-A4 above, the coverage area $\bigcup_\alpha U_\alpha$ contains the domain $\mathcal{D}$ if and only if the fence cycle $\mathcal{F}$ is null-homologous in $\mathcal{C}(\mathcal{U})$.*

This would appear to be exactly what one wants for sensor networks. Unfortunately, it is highly nontrivial to compute the Čech complex from the network graph Γ. One needs data on the precise distances between nodes in order to generate the higher dimensional simplices of $\mathcal{C}(\mathcal{U})$. We have two radii to contend with: the broadcast radius r_b and the coverage radius r_c. For no (physically realistic) choice of these radii can the radius r_c Čech complex be derived from the radius r_b network graph: see Fig. 3 for one example of the difficulty.

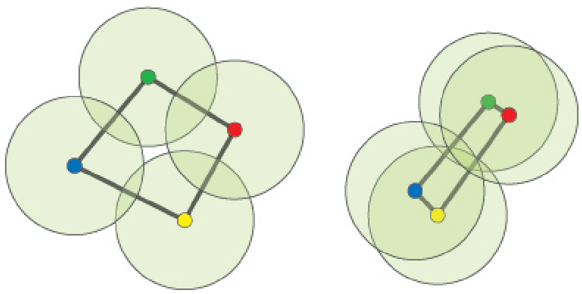

Figure 3: Changing the positions of nodes can change the topology of the radius r_c cover without changing the radius r_b network graph.

On the other hand, with the bound on coverage and broadcast radii in A2, it follows that for any triple of nodes which are in pairwise communication distance, the convex hull of these nodes in $\mathbb{R}^2$ is contained in the cover $\mathcal{U}$. The limiting case, in which all three nodes are at pairwise distance r_b yields an equilateral triangle in $\mathbb{R}^2$ which is covered by balls at the nodes of radius r_c only if $r_c \geq r_b/\sqrt{3}$.

This motivates the following construction. We consider the network graph as the 1-dimensional skeleton of a larger simplicial complex. Denote by $\mathcal{R}$ the largest simplicial complex whose 1-skeleton is the network graph. That is, for every collection of k nodes which are pairwise within distance r_b, we assign an abstract $k-1$ simplex. This is also known as the *flag complex* associated to the network graph.

A nearly identical construction was used by Vietoris in the 1930's in the beginnings of homology theory [14]. It was largely forgotten and later reformulated by Rips in his work on geometric groups [9]. Given a set of points $\mathcal{X} = \{x_\alpha\} \subset \mathbb{R}^n$ in Euclidean n-space and a fixed radius ϵ, the **Vietoris-Rips complex** of $\mathcal{X}$, is the abstract simplicial complex whose k-simplices correspond to unordered $(k+1)$-tuples of points in $\mathcal{X}$ which are pairwise within Euclidean distance ϵ of each other.

For brevity, we refer to the complex $\mathcal{R}$ constructed above as the **Rips complex** of the network, with the radius r_b understood implicitly. Unfortunately, the Rips complex does not necessarily capture the topology of the union of cover discs: we have traded accuracy for computability. However, for the remainder of this article, we will outline two methods for extracting coverage information from a Rips complex, the latter of which infers Čech data.

The homological criterion

The Rips complex does contain enough topological information about the cover to certify coverage, if the cover is sufficiently robust. One might guess that the right criterion measures $H_1(\mathcal{R})$, since $H_1(\mathcal{U})$ collates holes in the cover. For reasons to be seen, it is more natural to consider the second homology of $\mathcal{R}$ relative to the fence $\mathcal{F} \subset \mathcal{R}$ which defines $\partial\mathcal{D}$.

Theorem 3 ([4])**.** *For a set of nodes $\mathcal{X}$ in a domain $\mathcal{D} \subset \mathbb{R}^2$ satisfying Assumptions A1-A4, the sensor cover $\mathcal{U}$ contains $\mathcal{D}$ if there exists $[\alpha] \in H_2(\mathcal{R}, \mathcal{F})$ such that $\partial\alpha \neq 0$.*

The proof of this result is straightforward with an elementary knowledge of homology as in, say, Chapter 2 of [10]. We present an abbreviated proof.

Proof sketch. Define a simplicial realization map $\sigma : \mathcal{R} \to \mathbb{R}^2$ which sends vertices of $\mathcal{R}$ to the nodes $\mathcal{X} \subset \mathcal{D}$ and sends a k-simplex of $\mathcal{R}$ to the (potentially degenerate) k-simplex given by the convex hull of the vertices implicated. This σ takes the pair $(\mathcal{R}, \mathcal{F})$ to $(\mathbb{R}^2, \partial\mathcal{D})$. The long exact sequences on these two pairs yields the following commutative square:

$$\begin{tikzcd} H_2(\mathcal{R},\mathcal{F}) \arrow[r, "\delta_*"] \arrow[d, "\sigma_*"] & H_1(\mathcal{F}) \arrow[d, "\sigma_*"] \\ H_2(\mathbb{R}^2,\partial\mathcal{D}) \arrow[r, "\delta_*"] & H_1(\partial\mathcal{D}) \end{tikzcd} \quad . \tag{1}$$

The homology class $\sigma_*\delta_*[\alpha]$ is the winding number of $\partial\alpha$ about $\partial\mathcal{D}$. Observe that $\sigma_*\delta_*[\alpha] = \sigma_*[\partial\alpha] \neq 0$, since, by assumption, $\partial\alpha \neq 0$. By commutativity of Eqn. (1), $\delta_*\sigma_*[\alpha] \neq 0$, and thus $\sigma_*[\alpha] \neq 0$.

Assume that $\mathcal{U}$ does not contain $\mathcal{D}$ and choose $p \in \mathcal{D} - \mathcal{U}$. Since, by the choice of r_c, every point in $\sigma(\mathcal{R})$ lies within $\mathcal{U}$, we have that $\sigma : (\mathcal{R},\mathcal{F}) \to (\mathbb{R}^2, \partial\mathcal{D})$ factors through the pair $(\mathbb{R}^2 - p, \partial\mathcal{D})$. However, $H_2(\mathbb{R}^2 - p, \partial\mathcal{D}) = 0$: contradiction.

This homological criterion is sufficient but not necessary to verify coverage. The two networks illustrated in Fig. 4 both cover the domain completely. Yet the homological criterion holds for one [top] and fails for the other [bottom]. The culprit in the case of failure is a cycle of length four in $H_1(\mathcal{R})$. This creates a hole in the Rips complex which is not

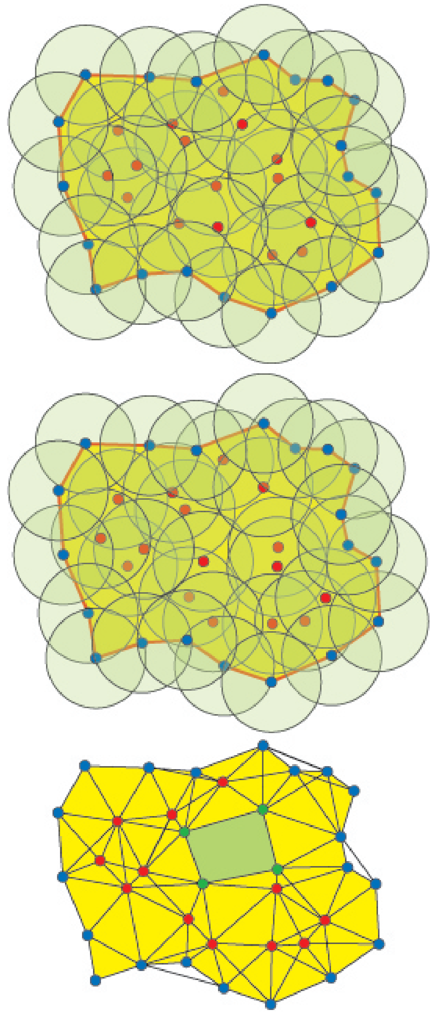

Figure 4: The homological criterion holds for some covers [top] but not for others [middle]. Failure is caused by a 1-cycle in the Rips complex [bottom].

present in the cover. Note, however, that a small change in the positions of the nodes implicated in this 4-cycle can create a hole in the cover without changing the topology of the network. No technique which relies solely upon the network topology can determine coverage in such a case. The homological criterion is effective for covers which are sufficiently robust with respect to perturbing the points while maintaining the network topology.

Generators for power conservation

The addition of some homological algebra to the sensor network can do more than confirm coverage. Indeed, it is a straightforward consequence of the proof that the domain $\mathcal{D}$ lies within the subcover of $\mathcal{U}$ generated by those nodes implicated in the generator $[\alpha]$.

For a sensor network which has a highly redundant cover, one can save power and bandwidth by placing non-essential nodes in a *sleep mode*. The crucial question: which nodes can be so deactivated without sacrificing coverage? In a dynamic setting, how does one cycle nodes from sleep to wake modes without losing coverage? The answer lies in choosing the appropriate "minimal" generators for $H_2(\mathcal{R}, \mathcal{F})$ which implicate as few 0-simplices as possible. Fig. 5 gives an example of a "small" generator yielding a more efficient cover.

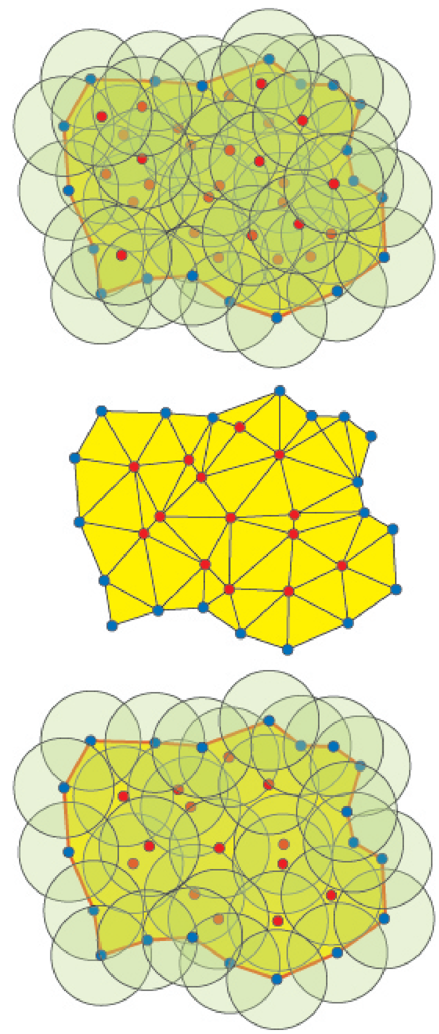

Figure 5: A redundant cover [top] can be simplified [bottom] by the appropriate choice of generator for $H_2(\mathcal{R}, \mathcal{F})$ [middle].

Pursuit and evasion

There are a number of related contexts in which a homological criterion can solve a global problem.

Consider the situation in which the nodes change position as a function of time. For simplicity, assume that the fence nodes are fixed. Such a situation might arise with sensors used to detect a forest fire, since one could establish a ring of fixed nodes outside the forest and allow the nodes inside the forest to be passively locomoted by environmental forces (e.g., animals).

It may well be the case that there are not enough sensors to cover the domain bounded by the outer ring. However, as the sensors change locations, holes in the cover can open and close in a complex fashion. The *evasion problem* for this scenario is whether an unknown *evader* can navigate through holes in the sensor cover without being detected. Even if coverage is never attained, one can still hope that any hole in which the evader begins is 'squeezed' out eventually.

To address this problem, one proceeds as follows. Assume that the network communication graph is updated at certain time intervals $0 = t_1 < \ldots < t_i < \ldots < t_N = 1$, producing an ordered sequence of communication graphs Γ_i, for $i = 1 \ldots N$. These induce a corresponding sequence of Rips complexes $\mathcal{R}_i$. We impose the following assumptions:

A5: If two nodes are connected at time steps t_i and t_{i+1}, then they remain connected for all $t_i \leq t \leq t_{i+1}$.

A6: Nodes may go off-line or come on-line, represented by deleting or inserting the nodes in the appropriate graph Γ_i.

A7: Fence nodes always remain fixed and on-line.

Given this sequence of network graphs (see Fig. 6), it is by no means obvious whether there is a wandering hole in the coverage network. We amalgamate the sequence of Rips complexes into a single simplicial cell complex $\mathcal{A}R$ as follows. For each $i = 1, \ldots, N-1$, let $\mathcal{R}_i \cap \mathcal{R}_{i+1}$ denote the largest subcomplex common to $\mathcal{R}_i$ and $\mathcal{R}_{i+1}$. This is well-defined since all vertices (and thus all simplices) have unique labels. We define the *amalgamated Rips complex* to be the quotient of the disjoint union $\coprod \mathcal{R}_i$ obtained by identifying $\mathcal{R}_i \cap \mathcal{R}_{i+1} \subset \mathcal{R}_i$ with $\mathcal{R}_i \cap \mathcal{R}_{i+1} \subset \mathcal{R}_{i+1}$ for each i. This yields a cell complex built from simplices, though not necessarily a combinatorial simplicial complex, since multiple simplices may share the same vertex set. Note that, given A7, the fence $\mathcal{F}$ is a subcomplex of each $\mathcal{R}_i$ and thus is identified to a well-defined subcomplex $\mathcal{F} \subset \mathcal{A}R$.

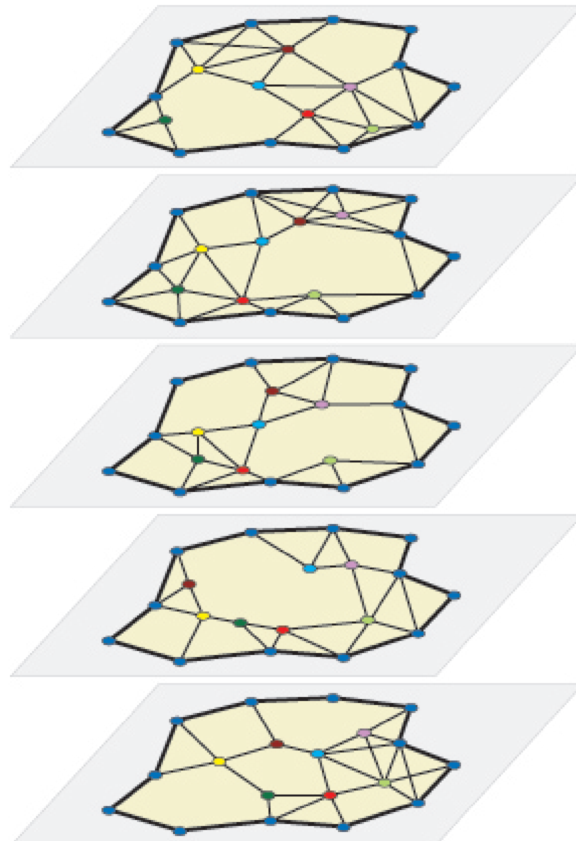

Figure 6: A time-sequence of network graphs for a mobile network. Does this network admit a wandering hole?

Theorem 4. *Consider a set of mobile nodes $\mathcal{X}(t)$ in a domain $\mathcal{D} \subset \mathbb{R}^2$ satisfying A1-A7. Given any continuous curve $p : [0,1] \to \mathcal{D}$, $p(t)$ must lie in the mobile cover $\mathcal{U}(t)$ for some $0 \leq t \leq 1$ if there exists $[\alpha] \in H_2(\mathcal{A}R, \mathcal{F})$ such that $\partial\alpha \neq 0$.*

The proof of this result is in the same spirit as that of Theorem 3 [4].

Persistence of homology

The ease with which Theorem 3 is proved is due chiefly to the restrictions placed on the fence nodes in A4. It is relatively easy to extend these results to domains which are not simply connected, to barrier coverage problems in 3-d, to systems with communication errors or variable radii [4], assuming one has control of the fence nodes. This control over the fence nodes is manifested in the proof of Theorem 3 in Eqn. (1), where $\sigma_* : H_1(\mathcal{F}) \to H_1(\partial\mathcal{D})$ is known to be an isomorphism.

Such control over the fence may be physically realistic in some settings where, say, one can explicitly build a ring of sensors around a potentially hazardous environment and then inject sensors in the interior of the domain. However, there are certainly settings for which a fixed ring of sensors is not possible. A more realistic setting is one in which nodes can sense if they are near the boundary $\partial\mathcal{D}$ and can register themselves as fence nodes. For example, a very coarse range-finder can detect the presence of a wall within a set distance, without necessarily knowing the distance to the wall.

We therefore consider a system of stationary nodes which can detect the presence of the boundary of the domain $\partial\mathcal{D}$ within some fixed *fence radius* r_f. This choice of system leads to a collection of fence nodes $\mathcal{X}_f \subset \mathcal{X}$ which spans a *fence subcomplex* $\mathcal{F} \subset \mathcal{R}$, the maximal simplicial complex generated by the fence nodes and edges between them. The analogous coverage criterion in this case should be the existence of a generator $[\alpha] \in H_2(\mathcal{R}, \mathcal{F})$ such that $\partial\alpha \neq 0$. Unfortunately, this is no longer sufficient for coverage. Consider the network in Fig. 7, in which the fence subcomplex $\mathcal{F}$ has a loop which is coned off to a disc in $\mathcal{R}$. This complex has $H_2(\mathcal{R}, \mathcal{F}) \neq 0$, yet the map $\sigma_* : H_1(\mathcal{F}) \to H_1(\partial\mathcal{D})$ is the zero-map, and Eqn. (1) is no longer useful in guaranteeing a cover. It is the existence of these *fake cycles* which complicates matters.

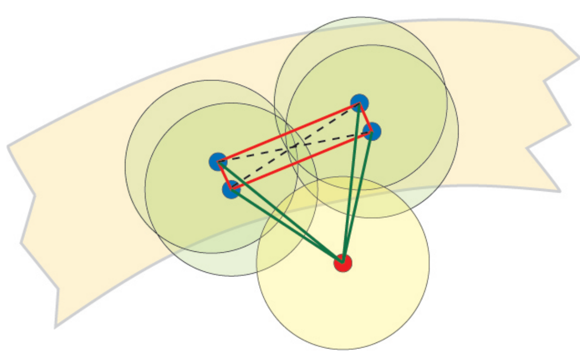

Figure 7: A fake relative 2-cycle in a system with a 1-cycle in the fence complex which is nullhomologous in the boundary collar.

There is a simple homological criterion for coverage in this setting where the fence nodes are not controlled [5]: it uses *persistent homology* and requires some additional capabilities on the part of the sensor network. The intuition behind this use of persistence is to note that the fake cycle of Fig. 7 could be detected as fake if the network could increase the broadcast radius a bit. Were this to happen, the 'diagonals' of the 1-cycle in the fence subcomplex would be filled in, killing the relative 2-cycle.

We can generalize this one example to deal with arbitrary fake cycles by allowing for two broadcast radii: a "weak" and a "strong" signal. This also has the advantage of generalizing easily to compact domains $\mathcal{D} \subset \mathbb{R}^n$ for any $n \geq 2$. The precise assumptions are as follows:

P1: Nodes broadcast their unique ID numbers. Each node can detect the identity of any node within radius r_s via a *strong* signal, or via a *weak* signal within a larger radius r_w, where $r_w \geq r_s/\sqrt{10}$.

P2: Nodes have radially symmetric covering domains of *cover* radius $r_c \geq r_s/\sqrt{2}$.

P3: Nodes lie in a compact domain $\mathcal{D} \subset \mathbb{R}^d$ and can detect the presence of the boundary $\partial\mathcal{D}$ within a *fence detection radius* r_f.

P4: The restricted domain $\mathcal{D} - \mathcal{C}$ is connected, where

$$\mathcal{C} = \left\{ x \in \mathcal{D} : \|x - \partial\mathcal{D}\| \leq r_f + r_s/\sqrt{2} \right\}.$$

P5: The fence detection hypersurface $\{x \in \mathcal{D} : \|x - \partial\mathcal{D}\| = r_f\}$ has internal injectivity radius at least $r_s/\sqrt{2}$ and external injectivity radius at least r_s.

The crucial feature is that sensors which are within signal detection range can distinguish weak versus strong signals, yielding a binary measure of in-range distance. The fence nodes are not controlled, but there is a need for (somewhat severe) restrictions on the shape of the domain so as to exclude pinching (P4) and wrinkling (P5).

Such a system gives rise to a pair of Rips complexes, $\mathcal{R}_s$ and $\mathcal{R}_w$, computed at the strong and weak radii respectively. Each is outfitted with a fence subcomplex, $\mathcal{F}_s \subset \mathcal{R}_s$ and $\mathcal{F}_w \subset \mathcal{R}_w$. There is a natural inclusion of pairs

$$\iota : (\mathcal{R}_s, \mathcal{F}_s) \hookrightarrow (\mathcal{R}_w, \mathcal{F}_w), \qquad (2)$$

since increasing the signal detection radius from r_s to r_w only increases network connectivity.

Theorem 5 ([5]). *For a set of nodes $\mathcal{X}$ in a domain $\mathcal{D} \subset \mathbb{R}^d$ satisfying P1-P5, the sensor cover $\mathcal{U}$ contains the restricted domain $\mathcal{D} - \mathcal{C}$ if the induced homomorphism*

$$\iota_* : H_d(\mathcal{R}_s, \mathcal{F}_s) \to H_d(\mathcal{R}_w, \mathcal{F}_w)$$

is nonzero.

The key which makes this theorem work is a squeezing theorem for the Čech complex. For a set of points $\mathcal{X} \subset \mathbb{R}^d$, let $\mathcal{C}_\epsilon(\mathcal{X})$ denote the Čech complex of the cover of $\mathcal{X}$ by balls of radius $\epsilon/2$. Let $\mathcal{R}_\epsilon(\mathcal{X})$ denote the Rips complex of the network graph having vertices $\mathcal{X}$ and edges between vertices within distance ϵ in $\mathbb{R}^d$.

Theorem 6 ([5])**.** *Fix $\mathcal{X}$ a set of points in $\mathbb{R}^d$. Given $\epsilon' < \epsilon$, There is chain of inclusions*

$$\mathcal{R}_{\epsilon'}(\mathcal{X}) \subset \mathcal{C}_\epsilon(\mathcal{X}) \subset \mathcal{R}_\epsilon(\mathcal{X}) \quad \textit{if} \quad \frac{\epsilon}{\epsilon'} \geq \sqrt{\frac{2d}{d+1}}.$$

Moreover, this ratio is the smallest for which the inclusions hold in general.

This is the type of result that is ideal for engineering applications. The Rips complex is computable, but does not give an accurate representation of the topology of the cover. The Čech complex gives the exact homotopy type of the cover, but it is not computable with the coarse metric information available. Theorem 6 tells how to infer Čech data from Rips data.

This technique of comparison between Rips complexes at two different scales ϵ, ϵ' is the simplest instance of a more general theory of persistent homology [7, 15]. This concerns the homological properties of nested families of topological spaces. Although the algebra and ideas involved are classical, the subject has been heavily driven by applications in computational geometry and nonlinear data analysis. Persistent homology is an algebraic topology for the 21^{st} century.

Theorem 5 is not the final word in homological coverage criteria for systems with a fence radius, and is best thought of as a proof-of-concept for homological methods. The hypotheses for this theorem flow from the mathematical details as opposed to the engineering details. For topological methods to make a serious contribution to security and sensor networks, it is important for the mathematics (and mathematicians) to work in conjunction with the engineers designing the sensor networks.

The homological coverage criteria surveyed here are the beginning of a larger foray of topological ideas in the theory of sensor networks, with plenty of work to be done. We note in particular the need for these coverage criteria to be distributed (so that networks can compute local homology and agree on global coverage) and asynchronous (so that updates to the network are not dependent on an instantaneous sampling of the network).

On computational topology

> "Topology! The stratosphere of human thought! In the twenty-fourth century it might possibly be of use to someone..." —
> *The First Circle*, A. Solzhenitsyn

The results we review here are but one branch of the rapidly evolving area of *applied computational topology*. The need to move from local to global is one which a large spectrum of engineers and scientists are finding to be prevalent. Very few of the calculus-based tools with which they are most familiar prove sufficient. Recently, it has been demonstrated that homology theory is useful for problems in data analysis and shape reconstruction [3], computer vision [1], robotics [8], rigorous dynamics from experimental data [13], and control theory [2]. See [11] for an overview of some current applications.

Topology is especially keen at giving criteria for when one can or cannot find a particular global object (a homeomorphism, a nonzero section, an isotopy, etc.): this falls under the rubric of *obstruction theory*. This perspective is one which has not yet permeated the applied sciences, in which the question, *"What is possible?"* is usually approached from the top-down, *"Here's something we can build,"* as opposed to the bottom-up approach that topological methods yield. A particularly good example of this obstruction-theoretic viewpoint in an applied context is Farber's use of topological complexity in robot motion planning [8].

In this article, we use homology theory to give coverage criteria for networked sensors which are 'nearly senseless.' It seems counterintuitive that one can provide rigorous answers for a network with neither localization capabilities nor distance measurements. Most topologist will not be surprised that such coarse data can be integrated into a global picture, but most engineers will. Our homological methods have the pleasant consequence that they may allow engineers to focus on designing miniaturizing simpler sensors which are nevertheless useful in a security network. Why bother miniaturizing GPS for "smart dust" if you can solve the problem without it? If topological methods can determine the minimal sensing needed to solve a global problem, then such methods may have significant impact on the way systems and sensors are developed and deployed.

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