A Quorum Sensing Pattern for Multi-Agent Self-Organizing Security Systems

Paper No. ICCST-2012-43

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Abstract—Swarm concepts of various types borrowed from nature have been proposed for multi-agent security approaches. Distributed decision-making in multi-agent systems is of particular interest, and has good application in large networks with end-point agents looking for anomalies and potential threat indications, which in isolation may mean nothing. Quorum sensing (QS) in bacterial systems and Honeybee nest-site selection are two examples of distributed decision making in nature that show promise for reuse in reaching collective conclusions and triggering action in networked cyber systems. This paper examines these two cases of QS in nature and abstracts a generic pattern that qualifies for self-organizing security according to six SAREPH characteristics covered in prior work. The pattern form and qualifying characteristics from this prior work are briefly outlined, and QS in the two different natural systems is shown to reach a tipping point based on the density of independent agents with relevant similarities. The inter-agent signaling mechanisms are shown to be central to the process, and the abstracted core pattern is discussed with the conflicting forces that have to be resolved in any application of the pattern. Illustrative examples of both deployed and proposed security approaches are then shown employing this pattern, along with a pseudo-code model for an appropriate signaling mechanism inspired by a paper on social network quorum achievement.

Index Terms—Bacteria, honeybees, mobile network, SAREPH.

I. INTRODUCTION

Drawing from examples in natural and man-made systems, Dove [1] describes an ongoing project to catalog patterns that could be reused in the engineering of self-organizing security systems. That project is identifying and describing self-organizing security patterns that might provide agility in system functional preservation on a par with the agility seen in the anti-system adversarial communities. This paper addresses one of the targeted patterns, quorum sensing (QS) – a means for a group of agents within a system of systems to reach collective decisions for action.

The pattern project utilizes a set of six characteristics to qualify a pattern for inclusion in the catalog, and established a standard format for describing the all such patterns The six qualifying characteristics are identified as Self-organizing [S], Adaptive tactics [A], Reactive resilience [R], Evolving strategy [E], Proactive innovative [P], and Harmonious operation [H]; and are referred to as the SAREPH characteristics. These characteristics are expanded in [1], and established from observation of the agile characteristics exhibited by anti-system adversaries .

As used by current researchers, the term *quorum sensing* denotes a means for a group of independent agents to reach common decision, and then to take collective action. Although the independence of each of the agents leads to the strength of the collective action, this independence also leads to a non-deterministic outcome, since a quorum may not be reached even when appropriate. A quorum could be prevented by various causes, such as insufficient density of agents, interfering communication noise, adversarial interference in the inter-agent communications, or adverse environmental conditions. If and when the tipping point of a quorum is reached, then the independent behavior of the individuals changes, and the group begins to act as a unified entity.

Observed examples of the QS pattern in nature are discussed first, then the pattern is abstracted into a standardized pattern form, next is shown an example of pattern application, and finally suggestions for where this pattern has practical application in security.

II. QUORUM SENSING IN NATURE

Two well-researched examples of quorum sensing in the literature of the natural sciences include bacteria and honeybees, revealing common QS-pattern characteristics as well as some differences. *V. harveyi* bacteria and honeybees will be discussed in terms of their SAREPH characteristics that qualify them for inclusion in the pattern project catalog.

A. Bacteria

The abilities of bacteria were once believed to be very simplistic and lacked one of the main capabilities that differentiate higher organisms, the ability to communicate and act as a group. This thinking was challenged by the research of Bonnie Bassler [2] and the *V. harveyi* bacteria. Bassler identified the methods by which the *V. harveyi* not only communicate but make collective changes in their behavior based upon the concentration of the group in the immediate area.

*Self Organizing***:** The bacteria secrete molecules, which are sensed by the nearby bacteria to both identify members of the same species and determine the relative concentration of peers in the immediate area. Once the concentration reaches a tipping point, all of the bacteria initiate collective action. Initially all bacteria function as individuals and exist in a benign state. When quorum is sensed, they all change behavior and self-organize into a unified entity to achieve a purpose, such as bacterial luminescence for night-feeding bobtail squid or releasing toxins in the human body.

Adaptive Tactics: The bacteria communicate intra-species, sensing and communicating with other bacteria types; adapting their tactics to an adversarial or cooperative environmental situation.

Reactive Resilience: Bacteria exhibit reactive resilience to cope with attacks on the underlying communication mechanisms. Defoirdt, Boon, and Bossiert [4] found that variability is seen in the signal molecule concentration, and the same species would show variability in the number of receptors present. This is theorized to be a natural reaction of the bacteria to stave off attack of the receptors by QS antagonists that compete with the natural signals of the bacteria. In another example by Miller et al.[5], the *V. cholerae* bacteria showed that deactivation of either or both of two main quorum-sensing circuits did not stop the bacteria from action expression (bioluminescence) during quorum. A third sensing circuit was discovered that provided complete redundancy for the failure of the primary sensing circuits.

Evolving Strategy: A variety of experiments [3, 4] indicate that QS in a given population of bacteria is capable of evolving, as the population grows, to overcome ineffectiveness (for whatever reason) in QS signaling and sensing mechanisms; and that this evolution occurs through selectively favored mutations in signal generators, signal sensors, and quorum triggers.

Proactive Innovation: The proactively innovative characteristic acts preemptively, perhaps unpredictably, to gain advantage. This is the typical purpose of QS in bacteria – individually waiting in quiet until the time when their population has grown large enough to succeed at a collective action that would be unlikely in smaller number.

Harmonious Operation: The behavior of *V. harveyi* to detect the concentration of its species and react through bioluminescence reveals the ultimate purpose of the microorganism – to work together in harmony to accomplish a common task as a large multi-cellular organism might in a similar situation.

B. Honeybees

Honey bees (*Apis mellifera*) use quorum sensing to find and establish a new nesting site. Bee colonies reproduce through budding, where the queen leaves the hive with a portion of the workers to form a new nest elsewhere. Studies by Seeley [6] reveal that after leaving the old nest, the workers form a swarm that hangs from a branch or any similar kind of overhanging structure. This swarm persists throughout the decision-making phase until a new nest site is chosen. Individual bee scouts have to communicate their preferences to each other, which have to be measured to meet the quorum. Communication is limited to a local level through a bee “dance”. Bee scouts that have found a good site dance with more intensity and for longer periods than do scouts that have found a less desirable site. As a result, more scouts travel to the better sites for confirmation. These new scouts explore the advertised nest sites, return to the swarm and report their findings. Continued confirmation skews the dancing in favor of better sites, until a group decision is made. Initiation of the swarm take-off starts prior to a consensus being reached, when the number of bees at the chosen nest site reaches a certain quorum level as observed by Britton et al. [7].

Self Organization: Honey bees achieve this collective wisdom by self-organizing themselves to capitalize on the collective knowledge even though each bee has limited information and intelligence as identified by Seeley and Visscher [8]. The individual bees are part of the group and not only contribute to the decision making process but abide by the quorum decision.

Adaptive Tactics: The tactics of the honey bee swarm are adaptive to changes in the environment as seen in [6]. The swarm decision to begin lift-off to a new nest is affected by both the concentration of bees at the chosen site as well as the weather conditions. If either of these conditions is not met, the scouts will suppress the production of the piping signals that encourage lift-off. This shows the ability of the group to both perceive and respond to the changing situation.

Reactive Resilience: The honey bee swarm must remain resistant to “noise” from bees that have identified a less-than desirable site. The change in the number of bees at a given site occurs slowly according to Diwold et al. [9]. This exhibits the resilience of the swarm to the introduction of false positives that could negatively affect the quality of the swarm’s decision.

Evolving Strategies: As the swarm identifies competing sites that are nearly equal in quality the swarm must break a dead-lock in their collective decision making. The concentration of the bees at multiple sites may be nearly equal, as will be the exuberance of their dance. In order for one site to win over the swarm, some scouts use inhibitory "stop signals", a short buzz delivered with a head butt to the dancer, to inhibit the waggle dances produced by scouts advertising competing sites according to Seeley et al. [10]. The vigorousness of the stop signal is proportional to the number of bees at a chosen site. The stop signal has either been co-opted to or from foraging, but in doing so its use has evolved; scouts use the stop signal to inhibit bees advertising different sites, and they do so because of the high, rather than low, quality of the site they have visited. Previously, the head butt had been observed to warn off foraging bees from dangerous areas (low quality) where rival bees or predators lurked. Evolving strategies such as this make the swarm stronger by enhancing the efficiency of the decision making process.

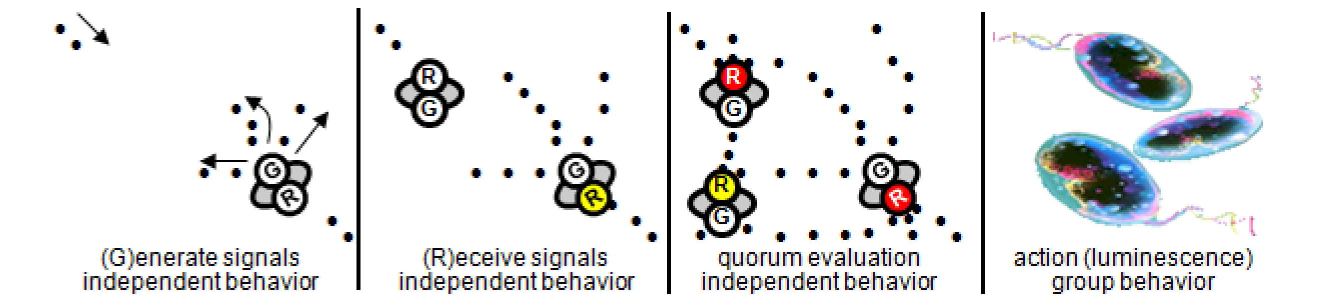
Proactive Innovation: The individual scout bees within the swarm not only proactively recruit new scouts to a promising site, but also show no tendency toward conformity or imitation of others as they contribute to the decision-making process, according to Seeley et al. [11]. The bees are in competition as they promote a given site and must be aggressive in the recruitment in order to give the swarm an advantage in site selection.

Harmonious Operation: The process of honeybee nest-selection QS occurs when the immediate pressing need is to decide upon a new nest site, and is thus harmonious with the needs of both the individual bees as well as the group.

III. THE QUORUM SENSING PATTERN

The reusable pattern is described in six elements: the context of the pattern, the problem that is mitigated by the behavior, the forces at work on the individuals and the group, the nature of the solution, a grounded specific example of the pattern being employed in a 4-panel graphic of pattern dynamics followed by the exhibited SAREPH characteristics of the grounded example, and finally, examples in the literature of pattern-employment in multiple domains. Table I displays and populates this pattern-description format.

TABLE I
QUORUM SENSING PATTERN FORM

Name: Quorum Sensing
Context: Agents in a multi-agent system that can broadcast and receive specific range-limited signals.
Problem: A need to ascertain when a sufficient number/density of specific agent signals indicate that a collective agent action is likely to be successful that could otherwise not be accomplished.
Forces: A useful agent action vs. the quantity or density of agents required to succeed; true signal recognition vs. false signals from noise and competing agents; sufficient quorum vs. inappropriate environmental conditions; high signal concentration in small environments vs. sufficient signal concentration in large environments; resource allocation to QS-driven collective-action achievement vs. resources needed for individual-action achievement; individual QS cost vs. collective benefit of QS action achievement; resilience of non-deterministic distributed control vs. efficiency of deterministic centralized control.
Solution: Develop an inter-agent signaling mechanism that generates and receives signals of action-interest that employs multiple strategies to guard against signal-interference and false influences.
 **Bacteria in light-generating organ of night-feeding bobtail squid create light when sufficient population exists.**
[S]elf-organized collective action occurs when a signaled quorum is sensed. **[A]**daptation occurs when individual signaling and sensing methods adapt to both environment and intra-species conditions. **[R]**eactive resilience occurs when redundant and variable individual signaling and sensing methods provide resilience to adversarial and environmental threat. **[E]**volution occurs when selective pressure causes signaling-ineffective individuals to evolve over successive generations toward signaling-effectiveness. **[P]**roactive innovation occurs when a quorum decision takes advantage of opportunity. **[H]**armony occurs when signaling and sensing processes enable decision-making in harmony with collective survival.
Example: Bacteria employ a quorum sensing circuit to identify the local concentration of the species and act toward collective outcome [2, 4]. **Example:** Honeybee scouts survey prospective nest sites and "report" in competition to the swarm until they reach a quorum on the quality of the site [6, 7, 8, 9, 10, 11]. **Example:** A general approach to decision-making in mobile social networks is described that enables group decision-making through local ad-hoc, peer-to-peer communications [12]. **Example:** In an analogous manner to these biological organisms, "cyber worms" lay quiet until the number of infected hosts is sufficient to trigger a collective attack [13].

The application of the QS method for group decision-making in security communities of practice as well as many other areas can lead to some innovative approaches. Ultimately, the independence of each of the agents leads to the strength of the decision made by the group. This distributed independence appears to be an important guiding principle in transference of the pattern to man-made systems.

The system must be able to react to external influences on the group and the environment. Adapting to these changes, the decision of the group may be postponed until the situation improves. Resilience against negative influences to the group protects the system from making bad decisions.

In order to guide quorum decision-making to the ultimate purpose, the strategy of individual agents evolves through successive generations to accommodate multiple, external influences. Proactively identifying ways to improve the efficiency of the process as well as the effectiveness of the final decision is a responsibility of each agent in the group.

Once the tipping point in decision-making is reached, the behavior of the group changes from one mode to another, and the group then acts as a unified entity. This ensures that the decision is both timely and pivotal to realize the overall collective objective.

IV. APPLICATION EXAMPLE

Practical application of QS requires establishing a common signal format. A common signal becomes the universal language between individual members of the group for decision-making. The components of the signal must provide enough information to enable them to evaluate a given decision, the number of other individual agents involved, and the tipping point (quorum value).

The signal that is generated for an artificial system may need to be more content rich than those examined here for bacteria and honey bees. In the case of bacteria, the signal molecules were very simplistic because the bacteria were "pre-programmed" for a specific task. They did not need to understand competing opinions, tipping points, or context. Honey bee communication signals were more complex than the bacteria as they needed to more accurately represent quality of nest sites, environmental conditions, and handle competing interests. An artificial system may take this to an even higher complexity level due to requirements of handling multiple tasks, more complex situations, and more rigorous time requirements.

Given these added requirements for the signal content, the elements that must be present will be further defined. This is going to be a more holistic approach to the problem that could be adapted to fit certain applications. For instance, a lot of the elements of the signal could be pre-programmed into each agent, thereby simplifying the message structure.

In work by Agrawal [12] a general approach to decision-making in mobile social networks provides the basis of the signal. The premise of the [12] is to devise a plan for enabling group decision-making through local ad-hoc, peer-to-peer (P2P) communications. This is an interesting concept and adheres to the principles that were discussed in the bacteria and honey bee examples. The signal content in [12] was adequate for fairly binary decisions, but this will be expanded here to handle decisions that require measures of quality similar to nest site selection with the honey bees.

Based on the ballot (signal) [12], Table II represents the basic fields of the quorum-sensing signal (in JSON format).

The first field in the *qsSignal* is the *decision* that is proposed for quorum. This is necessarily shown as a free text description for this example, but would likely be one of a pre-determined set of decision types. *Expiration* is important for applications that are time sensitive, for instance a UAV that is low on fuel. Each peer in the group may provide a *suggestedValue* representing their "vote" on the decision.

The next four fields were added to provide a necessary measure of quality reminiscent of the way honey bees advertise the suitability of a given nest site to the swarm. The *qualityMeasure* field defines the measure by which the decision should be evaluated. While this example shows only one set of quality fields, these could be expanded to encompass a number of qualitative measures. Next are the *qualityUnits* by which the *qualityMeasure* is represented. Of necessity in an artificial system is the *qualityThreshold* that the *qualityMeasure* must exceed or an acceptable range of values. The final quality field is the actual *qualityValue* of the *qualityMeasure*.

The *quorumValue* quantifies the tipping point for the system. The *quorumValue* must take into account the total number of agents in the system as well as the number needed to adequately evaluate the decision. Since the system communicates P2P with no master agent, the originating peer needs to keep track of the *suggestedValues,* associated *qualityValues*, and the ***unitIds*** that have suggested each value – ***acceptedValues***.

The last three entries of the *qsSignal* uniquely identify the specific decision – *uniqueId*. the individual agent that originated the decision – *originatorId*, and a specific agent – *voterID* – that is participating in the decision by sending this *qsSignal*.

TABLE II
JSON QS EXAMPLE FOR UAV LANDING-SITE SELECTION

```
qsSignal{
decision: "Selecting a landing site for a UAV",
expiration: "2012-05-24 10:00:00",
suggestedValue: "Coordinates N39º34.21' W104º50.96",
qualityMeasure: “Length of runway”,
qualityUnits: “meters”,
qualityThreshold: “1200”,
qualityValue: “1463.04”,
quorumValue: 10,
acceptedValues: {
" Coordinates N39º34.21' W104º50.96, 1463.04": [31083,
13091, 38919, 900941, 109381],
" Coordinates N39°43′11.51 W104°53′43.45, 1211.21":
[13134] }
   uniqueId: 107074168843,
   originatorId: 31480,
   voterId: 900941
}
```

An originator of a proposal sends the qsSignal out in a broadcast to local peers. A peer has five options to take when receiving the qsSignal:

1. *Accept* – the peer reads the qsSignal, relays the qsSignal, interprets the decision, evaluates the suggestedValue against any known values by comparing qualityValues/qualityThreshold, and accepts the suggestedValue. Peers that accept the qsSignal record the uniqueId so that future qsSignals they receive with this uniqueId will be broadcasted. The qsSignal is broadcasted back to the originator.
2. *Broadcast* – the peer receives the qsSignal and determines if they have already assessed the qsSignal. If they have, the signal is broadcasted.
3. *Proposal* – if the peer determines that the suggestedValue does not meet the qualityThreshold, or it has a value that is of higher quality, then the peer will propose a new suggestedValue. The qsSignal that is sent out must contain the new suggestedValue, the corresponding qualityValue, and its voterId.
4. *Ignoring* – the peer can choose to ignore the qsSignal if they have no relevant information available about the decision. The peer should record the uniqueId and only perform a broadcast or rejection on this specific qsSignal in the future.
5. *Rejection* – the peer chooses to reject the qsSignal as invalid if there is any corruption or the expiration has

been exceeded. The agent should record the uniqueId and performs a rejection (delete the message) on this specific qsSignal both now and in the future.

This qsSignal format is not meant to be universal. There may be situations that require additional control, descriptive, or qualitative fields. However, the presented model should accommodate a large number of simple decision frameworks.

V. SECURITY APPLICATION POTENTIAL

The mobile social networks example described above has an application analog in intelligence data mining, where a community of intelligence agents are finding locally suspicious indicators in personal data mining activity that needs quorum concurrence in a global community to warrant a response action. Also, a cyber security analog to the mobile social networks example might be in anomalies detected by local anomaly-detection agents that require confirmation and agreement by other agents before an intrusion response is warranted.

The Internet Storm Center practices a form of QS. From their *ISC History and Overview* document at http://isc.sans.edu/about.html the core elements of QS at work are seen:

> "On March 22, 2001, intrusion detection sensors around the globe logged an increase in the number of probes to port 53 â€" the port that supports the Domain Name Service. … Within an hour of the first report, several analysts, all of whom were fully qualified as SANS GIAC certified intrusion detection experts, agreed that a global security incident was underway. They immediately sent a notice to a global community of technically savvy security practitioners asking them to check their systems to see whether they had experienced an attack. Within three hours a system administrator in the Netherlands responded that some of his machines had been infected, and he sent the first copy of the worm code to the analysts. The analysts determined what damage the worm did and how it did it, and then they developed a computer program to determine which computers had been infected. … Just fourteen hours after the spike in port 53 traffic was first noticed, the analysts were able to send an alert to 200,000 people warning them of the attack in progress, telling them where to get the program to check their machines, and advising what to do to avoid the worm."

Though there is an element of centralized control not present in classical QS, this approach that sends action capability to a large number of agents who don't posses that capability inherently is an implementation detail necessitated by the nature of ever-changing attack characteristics. Those that receive and act on counter measures in effect evolve new capability and are thereafter capable of initiating that action locally.

The US intelligence agencies have Intellipedia, a wiki for sharing information among the agencies. Using real time incident page-entries, multiple agencies can compare related notes and reach conclusions about correlations that lead to quorum agreement and the decision for collective action. Though this QS-like collective decision-making doesn't appear to be an integral part of the Intellipedia usage practice as yet [14], it is nevertheless a latent capability awaiting recognition and employment automation.

Vogt, Aycock, and Jacobson [13] have suggested and simulated a way that the adversary could use QS to engineer a self-stopping worm. Self-stopping once a sufficient number of nodes are infected makes a worm more difficult to detect. They examine both QS and non-Qs approaches for a worm to determine when to cease further infections, and show that the QS method provides advantages over the non-QS methods that were compared. They conclude with some discussion of possible countermeasure approaches in need of further study.

VI. CONCLUSION

The authors are disappointed but not surprised with their inability to find overt QS methods applied to the security arena as yet. Self-organizing security methods are in their infancy, and in need of study, prototyping, testing, and socializing before they can be accepted. The QS pattern described in this paper, and companion patterns of other self-organizing security concepts from natural systems, are in an early stage of cataloging [1, 15, 16, 17, 18], with the intent to remove the barriers toward acceptance.

The QS pattern should be useful in bringing together communities of practice in the security arena, to deal with emerging threats as well as discovery of correlated intelligence information that can lead to conclusions and actions, and to help in correlating and classifying network-distributed anomaly detection as intrusions in process.

Ultimately, the independence of each of the agents leads to the strength of decisions made by the group. Once the tipping point in decision-making is reached, the behavior of the group changes into unified action. Further refinement of the QS pattern should uncover a rich set of practices and operational scenarios that can utilize QS.

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VIII. VITA

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