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COMMUNICATION COLLECTIVE: AN ADAPTIVE MULTIAGENT COMMUNICATION PLATFORM

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ABSTRACT

A robust, consistent and high-capacity data network is critical in modern society to ensure that governments, businesses and individuals are able to communicate and coordinate disaster relief, just in time deliveries, or to organize how and where to meet friends. Existing terrestrial communication networks are susceptible to being disabled or destroyed by disasters and the use of satellites is costly and inflexible. We propose a communication protocol, called Communication Collective, to operate in a resource constrained, dynamic and contested environment with distributed, learning, adaptive, predictive, mobile agents. Each agent operative gathers information from the environment and the surrounding Communication Collective and independently weighs its options on how to behave to improve the performance of the collective. Our experimental analysis shows the potential of our approach, with improved delivered messages and significantly reduced latency.

1 INTRODUCTION

It is critical for many applications to have robust, consistent and high-capacity data communications (Roller and Waverman 2001) and numerous technologies to provide the required communication capabilities are available. Many are built upon wired internet connections for example using DSL, fiber or cable. Satellite technology has also been able to create worldwide communication coverage, creating capabilities in isolated environments and enabling ships and aircraft to keep in contact no matter where their location on the Earth. More recently, fixed wireless technologies have dramatically altered the communications world, with different generations of cellular and Wi-Fi networks expanding the way we communicate. Given the ubiquity of network attached devices, the wireless medium needed to provide these services have become highly sought after, with proposed ways of trying to increase data carrying capacity of this limited resource (Staple and Werbach 2004).

All of these communication platforms have a number of drawbacks. Firstly, they are based on fixed infrastructure and thus may be susceptible to being disabled, damaged or destroyed when faced with natural disasters, such as bush fires, storms and earth quakes (Çetinkaya et al. 2013; Jang et al. 2009) as they cannot be easily or cheaply moved to safety. For example, in September 2016 storm damage caused central business district and metropolitan areas in Adelaide to lose power (Australian Associated Press 2016), causing the communications infrastructure to fail and leaving people without means to call emergency services (Charis 2016). Fixed infrastructures are also susceptible to deliberate disruption whether in a military conflict or due to acts of terrorism.

Secondly, fixed communications infrastructures are unsuitable in dynamic, contested environments. In a military context, there are many scenarios where reliable and timely delivery of message and data

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communications are required (Đurišić et al. 2012; Lee et al. 2009). Fixed communications infrastructures cannot be relied upon as they can easily be disrupted or damaged by a military or guerrilla opponent (Kwak and Borghetti 2010). The military context itself may involve a dynamic, contested communications environment. Thirdly, fixed wireless networks are a shared medium in which the distribution of the available resources may lead to shortfalls in capabilities. This could be due to miscalculating the actual demand on installation, or their deployment in environments with limited infrastructure due to natural or man-made disasters (Jang et al. 2009). There is a need for a communication protocol that overcomes these limitations, to deliver timely messages with a good quality of service in a dynamic, distributed and contested environment.

Other current approaches attempt to create a communication network in an environment where fixed infrastructures do not exist or have been destroyed. For example, replacement or temporary communications infrastructure or the use of communications satellites can be utilized, cell on wheels (COWs) which are mobile 4G base stations can be used where there has been a break down in infrastructure. Each of these provide some benefit but each has significant limitations. Ad-hoc networks are networks in which the network's control is distributed amongst the network users.

While ad-hoc networks can be created, most consumer devices, e.g., mobile phones, are not created with this functionality in mind. Users and vendors may be reluctant to let other users relay data on their devices. For the few devices that do have this ability, their transmission power/range is usually limited due to privacy and security considerations, requiring devices to be in close proximity to one another. Thus stationary, out of range devices cannot participate in an ad-hoc network. Replacement or temporary stationary communications equipment may have been affected by the same problem that destroyed the original infrastructure.

Existing approaches have not yet addressed all the challenges within this space, and as such, for a solution, we propose the use of agents (Weimer et al. 2017), as they have the mobility, autonomy, redundancy and flexibility to create a communications network to meet these requirements.

The creation of an autonomous intelligent acting agent has been the focus of much research. This includes focusing on how agents gather and represent information from their environment. Agents, in addition to reacting to stimuli, consider their actions with respect to their goal and plan a course of action. For agents to interact with their environment, they need to be able to manipulate objects and navigate unassisted (Johnson et al. 2015). In addition to methodologies for communication, command and control for a large number of agents have also been analyzed (Howard 2013).

In this paper we propose a communication protocol to operate in a resource constrained, dynamic and contested environment with distributed, learning, adaptive, predictive and mobile agents. The radio spectrum needed to communicate both messages and organization information for the agents is constrained, requiring balancing of the frequency resource to allow its efficient use. The operating environment is considered to be dynamic, with devices moving around and requiring changing levels of service. The agents will be considering the environment to be contested either actively or passively, being jammed or needing to share the radio frequency spectrum with other devices. Agents are required to be mobile and they need to move, adjusting the network shape to suit clients' needs. Agents need to adapt the network topology and performance based on temporal client demands, allowing higher bandwidths for specific continuing communications between clients, while still providing required service to all others. It is not always possible to provide the required service when needed as it can take time to adjust the network, however if agents have the ability to predict future demands based on prior use then it is possible to pre-emptively prepare for the demand.

Network state information needs to be partially distributed among the agents to ensure redundancy and scalability.

Complete knowledge sharing between agents would flood the communications network (Gautam and Miyashita 2007) leading to reduced performance. In addition, the agents' memories are finite. Finally, the ability to pre-program the exact norms and procedures an agent should follow and to ensure they are correct is a non-trivial task (Gilbert 2004), as the agents must be able to learn to modify their behavior to better suit the environment and create a better network. The contributions of this work are twofold:

- A new agent-based communication infrastructure working in dynamic contested environments through coordination and cooperation.
- An extensive experimental analysis highlighting the need and extensive benefits of our work.

2 RELATED WORK

In order to function in a contested and dynamic environment, agents need to be able to position themselves in a way that facilitates communication over a network. We categorize related research into two broad categories to facilitate understanding: *positioning*, focused on how the agents organize themselves within a physical space and *network*, focused on problems associated with a dynamically changing distributed network. We discuss these below.

2.1 Agent Positioning

Agents are positioned with respect to the environment and each other and this determines characteristics of the communication network they create. The perfect network would need to service the largest possible area with the fewest number of agents, in addition to providing the highest possible bandwidth to the network users, leading to trade-offs between these two goals.

Beacon systems (Scheutz and Bauer 2006) discussed a simple method for spreading out an agent intrusion detection network with the use of two beacons on each agent. The first beacon was used to geographically position the agents relative to each other, and the second beacon to signal a detected intrusion. Each agent could simultaneously transmit and receive beacon messages. The message strength decreases as the agent travels away from the transmitter. Using message strength agents can determine how far away they are from each other. Agents use the first beacon's signal strength to find a 'sweet point' of how close they should be to their neighbors. If the signal strength is too high, then agents should move away from the signal, causing the communications network to spread out. To keep the network together when the signal strength is too weak, agents will move towards the signal thus causing its strength to increase (Howard et al. 2002; Scheutz and Bauer 2006). The second beacon works as a signaling relay that is used by the agent when an intrusion is detected. The message is repeated by all agents within transmission range. The main benefit of the beacon system is the simplicity of the rules, as they are relatively easy to encode and require little processing power to follow. As the rules try to find a geo-spatial agent density equilibrium, a side effect is the self-healing ability of the network as agents will move to fill a noticed gap in the network.

However, the network has no concept of its environment and thus it is unable to take exploit it. In addition, the network shape, which is determined by the rules, converges to a circular clustering. Often in intrusion detection systems, it is beneficial to take advantage of the environment and create detection parameters which take a more elongated topology.

Relying on network users An opportunistic network is mentioned by (Roy et al. 2018) where the agent's positioning is not influenced by the wireless network that can be created. For example, in a disaster area, information can be placed into a car, or the mobile phone of an aid. As the devices moves from one camp to another, information can be disseminated (Roy et al. 2018). While the system uses the movements of existing actors to facilitate communications, it has no direct control over their behavior. No direct communication is possible, as the network is used to delivering conceptual parcels of information between points with no guarantee they will be delivered.

Inter-agent communication Batalin and Sukhatme (2003) and Pezeshkian and Nguyen (2006) proposed that agents form a *bucket brigade* to provide wireless network connection. Initially, all agents would move together away from the source of wireless connection. When the network strength drops to a certain level, an agent would remain behind to be a network relay, thus allowing the others to move further away but still remain in network range (Batalin and Sukhatme 2003; Pezeshkian and Nguyen 2006). This approach allows agents to explore the furthest distance away from the initial network connection, as agents pass messages along the chain thus maximizing the linear distance the network can stretch. Instead of having semi-independent agents making up the network, the *bucket brigade* acts as a single entity, servicing the head of the chain to communicate back to the starting location. However, the approach is not fault tolerant as the failure of an individual agent breaks communications to the head of the chain. In addition, the communication load is not evenly spread over the agents.

To allow for more complex positioning, communication between agents is required to facilitate coordination in both their current and past geographical positions. One way of representing this information is by pheromone maps (Parunak et al. 2003; Sauter et al. 2008). These require agents to record their taken actions onto a shared or distributed ledger that also retains geographical information. Other agents can adjust their behaviors based on this information. The action recorded on the ledger changes and deteriorates over time, allowing stale information to leave the system. This method allows simpler reactive agents to be designed, with their behavior following rules based on the state of the map (Sauter et al. 2005).

While a pheromone map makes the decision process for the agents easier, its existence adds complexity to the system. Firstly, to use the pheromone map, agents need to know their precise geo-spatial location, and to read and write pertinent information. This requires the agent to have a method of knowing their location. This could be done with the use of GPS. Secondly, agents need access to the pheromone map to be able to use it. Having a central repository would prevent the system from scaling as communication with the map will become a bottleneck. Thus, a distributed approach is required, which would keep an up-to-date, regionalized distributed pheromone map, where the required information is shared among the agents.

2.2 Network

Computer communication can be viewed from two perspectives, physical and logical. The physical refers to the sending and receiving of information as bits through a medium, be it wire, optic fiber or radio frequency. It is concerned with message deterioration, interference and maximizing the number of bits sent and received. The logical is based on top of the physical network and is concerned with the conceptual problem of how to move a message between agents in the network to reach its destination. The physical perspective is important as everything is reliant on it, however there are problems associated with wireless networks.

A mobile ad-hoc network (MANET) is made up of a set of interconnected mobile agents. Each agent acts both as a receiver and transmitter, enabling each to communicate wirelessly with its surrounding agents, including the ability to route messages for agents out of direct transmission range (Lalar 2014). The logical network topology of how messages are routed through the network change as agents move, potentially causing a situation with no route between agents. This intermittent connectivity causes the need to develop a delay tolerant network (DTN) that can store a message until a new route is established (Kuiper and Nadjm-Tehrani 2011; Roy et al. 2018). A benefit of this approach is it can partially hide the network instability from the applications using it, as the routing protocol deals with holding onto the messages until connection is re-established.

However, such benefit comes at an increased cost to the communications network. There is limited space for storing messages, and as such decisions need to be made about where in the network the messages will be stored and whether a bottleneck will be created from a flood of waiting messages upon restart (Gautam and Miyashita 2007). Another decision refers to what should happen if the recipient does not rejoin the network with applications still needing programming to handle possibly delayed messages. This method also assumes routing knowledge exists as to whether holding onto the message for later delivery is required or not.

Other approaches' shortfalls are considered when developing the Communication Collective. The agent mobility can give protection from the initial disaster or attack as they can move to safety. This movement also allows adaptability to the communication platform thus maximizing the network's coverage, or ensuring clients remain within range. Changing the message routes also affects the available bandwidth in different sections of the network. Operatives are self-contained determining their role and behavior by the behavior of clients and the network. This allows the network to scale without the creation of control bottlenecks. As the network is made up of multiple individuals it increases its reliability. There is redundancy if some individual is damaged as well as making the network harder to jam with higher power local transmissions.

3 PROPOSED APPROACH

The existing work has drawbacks when being applied to a distributed communication platform: fixed infrastructure is fragile and can easily be damaged or destroyed and satellites are expensive and have limited bandwidth for numerous point to point communication. MANET and opportunistic networks have little to no control over whether a message is successfully delivered or not. The Communication Collective is a collection of independent mobile agent operatives that work together to create a communication platform that clients use to send messages to each other. Collectively operatives and clients are referred to as participants. The Communication Collective is comprised of comparatively cheap multiple mobile components so the network size can be scaled as required. The operatives' mobility allows them to move out of disaster's way, move the network to where they are required and allow redundancy if aspects of the network are damaged or jammed.

Each operative interacts with the environment via three different means: sensors, its movement, and communications. *Sensors* determine the operatives' location in the world and items within sensor range, be it other participants or the physical environment. There are two uses for communications. The first use is to forward client messages towards their destination. The second use is to pass information between operatives regarding the network state. Movement of operatives allows message routing pathways to change as they move closer or further away from each other and to keep clients within range of the network.

The operatives are independent of each other, and their characteristics are summarized in Table 1.

Table 1: Operative.

Inputs	
Sensors	The positioning of the operative in the environment.
	Location of the operative with respect to other operatives.
	Radio frequency noise.
Communication	Receiving client communication.
	Receiving network status and configuration information.
Outputs	
Movement	Facilitate routing messages through the network.
	Keeping clients within communication range.
	Moving to avoid or mitigate jamming.
Communication	Sending client communication.
	Keeping clients within communication range.
	Sending individual and collated network status and configuration information.

Figure 1 shows how the data flow is grouped into six categories. These are:

1. *Input* is received into the operative from either its sensors or participant communication.
2. *Raw Data* groups and collects information received from the inputs.
3. *Collated Data* uses the raw data to build a model of the operative's environment, the network's state and what messages it has to deliver.

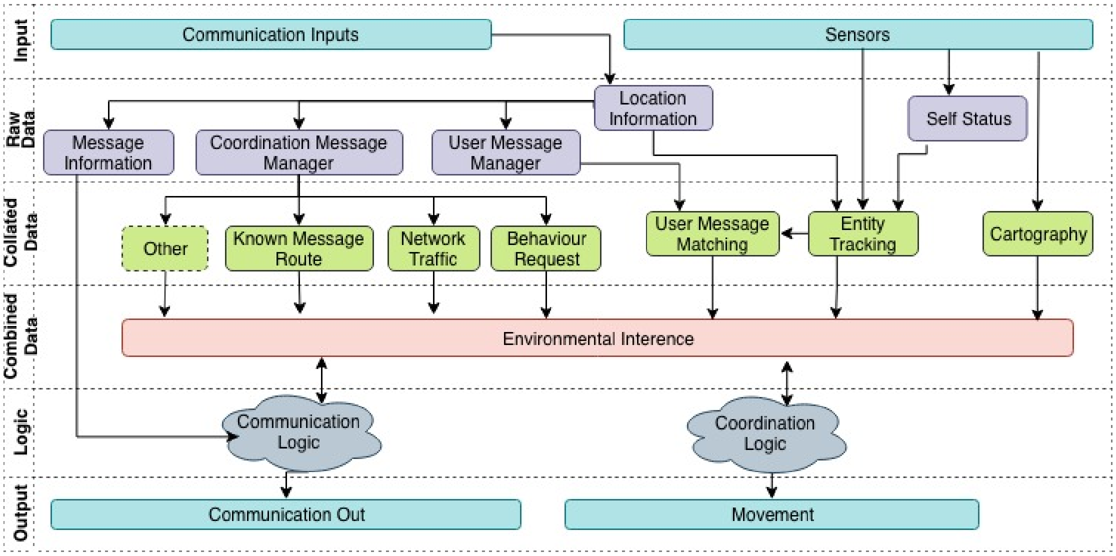

Figure 1: High level internal structure of an operative process flow from inputs to outputs.

4. *Combined Data* is a central location within each operative where it collates the data it has access to, giving a singular view of the environment so it can be queried when determining the future actions of the operative.
5. *Logic* is broken into two components, namely Communication Logic and Coordination Logic. The Communication Logic is in charge of working out how to process client messages with respect to knowledge of the environment and who is in communication range. The Coordination Logic is interested in constructing a model of the network workloads, client locations and movements, then decides where the operative should move and how it should act to maximize the network's performance.
6. *Output* is the way the operative interacts with the environment.

Operatives interact with each other directly via communication and indirectly by their detected relative positioning. Operatives that interact directly via communication forward messages over the platform and can send coordination messages. Coordination messages are used to share knowledge of the state of the Communication Collective between operatives. Operatives that interact indirectly by detecting other operatives though sensors can change their perception of the environment and thus its behavior.

An overview of the operative's decision-making methodology is shown in Figure 2. The model follows the concept of a belief, desire, intention (BDI) system (Bratman 1989). *Belief* is the internal representation an agent has about itself, the world it is within, and possibly any information given to it by an outside actor, such as a human or from another agent. It uses this information to reason about the world, what has happened and what it believes is likely to happen in the future. *Desire* is focused on the goals of the agent, what does the agent wish to achieve by being, be it to maneuver to a certain location, remain standing or manipulate the environment, such as move objects or operate machinery (Johnson et al. 2015). *Intentions* are what the agent has decided to do, a set of procedures it believes, when followed, will help satisfy or accomplish its goals.

The belief of the operative's interaction with the current situation within the simulation is drawn from two sources, namely, the current role that the operative is following and the operative's perceived store of information from its environment inference.

Recalling the role with historic information allows for consistent behavior over time, as task completion is preferable to swapping between multiple non-completing tasks. These memories are used in perceived benefit calculations in determining its actions. The quantity and duration of memories to achieve collective

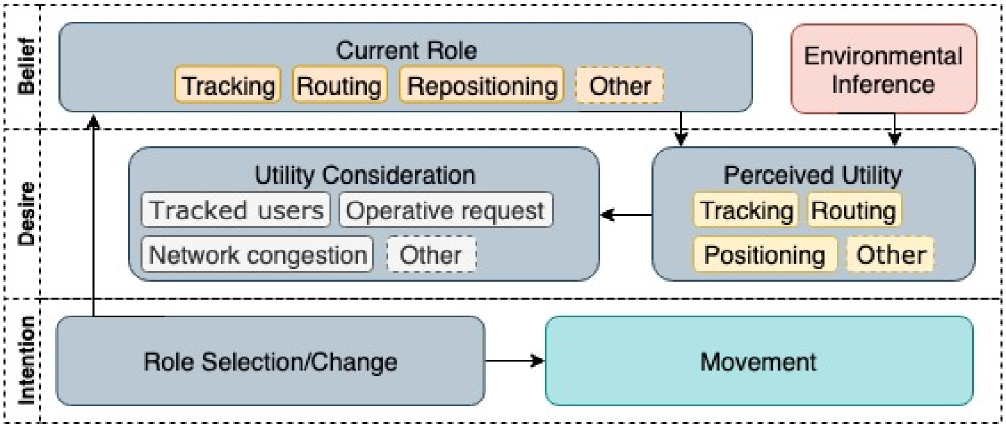

Figure 2: High level internal operative internal consideration flow.

performance improvement as well as what is an appropriate level of improvement to the increased costs of hardware and processing complexity, remain an open question.

The current perceived state of the world found in the environmental inference comes from an amalgam of its sensors and information passed to it from other operatives. Although in this system we are not considering intentionally false or misleading information, the information could be out of date and this needs to be accounted for. The desire of the operative is to maximise the Communication Collectives functionality. There are two steps in determining desire. The first step calculates its perceived utility to the Communication Collective of the operative adopting different roles. This is stored as a weight. Roles include (i) *tracking* a client so they remain within communication range, (ii) *positioning* itself with respect to other operatives to improve/maintain communication area coverage, and (iii) *enhance* routing between clients. The second step, utility consideration, modifies the possible role weightings depending on the current state of the known Communication Collective. Points of consideration include which users are currently being tracked by other operatives, the current communication network congestion and possible other operatives' requests. The intent of the operative is to carry out changes it can make to the environment to facilitate the role it has selected, and thus define where and how fast it will try and move within the environment. The only role operatives can currently choose from is to continue to move in a straight line within the environment.

The objective of the Communication Collective is to create a communications platform that allows clients to communicate with each other. Clients exist in the simulation to use the Communication Collective but are separate from it, as the network has no control over their behavior. All aspects of clients, such as speed, communication range and data rate are independent from the operatives.

4 EXPERIMENTAL ANALYSIS

In the prototype implementation of the Communication Collective, several aspects are random, from the starting location of participants to a client that will create a new message and decide to whom it should be sent. The random aspects are created from the Mersenne Twister pseudo random number generator, which is given an initial seed value. Several modules need still to be implemented, namely, having individual operatives create and maintain an expanded model of the environment, in order to understand their location with respect to clients and other operatives. From this model, planned routing mechanisms can be applied defining which operatives handle the forwarding of messages between specific clients, thus reducing the bandwidth requirement. Another module to be implemented refers to an operative's positioning planning, which determines how agents move depending on the network communication load and the positioning of other operatives and clients within the system.

Each trial in an experiment is repeated twenty-five times with different initial seed values. We assume our averaged results will approximately follow a normal distribution and thus in each experiment we calculate averages and population standard deviations. Confidence intervals of the results are shown in the tables are calculated at approximately 90% in the format '[lower-upper]'. We understand the mathematics used for calculating confidence intervals around an upper limit become unreliable, however they are still useful in showing trends between experiments.

In the following experiments inputs are changed and trials are made to determine the performance of the Communication Collective. Inputs include participants, the number of operatives and clients within the simulation, with ratio describing the number of operatives per client. *Message density* is a probability applied to each client per second that determines if they will generate a new message to be routed through the Communication Collective. The *world dimensions* is a three dimensional area representing the simulation world described in width, height and depth in kilometers. This world space has a hard edge, with all participants originally created within this space and are unable to leave this space. Participants are able to identify each other along with their location and obstacle. Communication is limited to the lesser ability between the two participants, using the minimum data rate (bytes) and distance (km) of the two. The current model uses a binary cut off: either they are within range and can communicate at the full data rate, or there is no communication. Messages have a size made up from header information as well the body, thus it takes time for a message to be transmitted between participants. Participants can move around their environment with a maximum possible speed measured in meters per second. *Message buffer size* is the number of messages an operative can store at the same time.

The following metrics are calculated: area coverage, client coverage, message hop count, messages received, latency as well as movement of clients and operatives. *Area coverage* is the percentage of simulation area covered by at least one operative's communication range. This percentage is estimated by splitting the simulation area into $250m^3$ cubes, with each cube marked as covered if it is fully within range of an operative. *Client coverage* is a percentage measurement of the number of clients within communication range of at least one operative. *Hops* is a count of steps a delivered message took to reach the destination client, as each message needs to pass through at least one operative the smallest hop number is two. *Messages received* is a percentage calculated by the successfully delivered messages divided by the total number of messages created within the simulation. *Latency* is how long it took for messages to reach their destination; the time is from its creation till delivery. *Client and operative movement* are an average measurement of how far they moved per second within the simulation.

4.1 Effect of Participant Density

In this experiment, we evaluate the performance of the communication collective as the number of participants increases, using the experiment parameters shown in Table 2.

Table 2: Experiment parameters unless otherwise defined.

Property	**Value**
Participants	300 Operatives and 30 Clients
Communication rate	5 kilobytes per second
Message Density	Each client has 1% chance per second
World Dimension	100 x 16 x 50 km
Communication distance	8km
Message Buffer Size	50 messages per operative

We show our results in Table 3. There is a fixed sized environment within the simulation, thus as the participant density increased it changed several statistics. Firstly, the communication area covered by the operatives increased along with the client network coverage. Secondly, the number of generated messages grew proportionately to the client count. Thirdly, the number of hops grew indicating at lower

Table 3: Participant density results.

Operatives and Clients	Messages Generated	Area Coverage %	Client Coverage %	Hops	Messages Received %	Latency (s)
50 : 5	[481-497]	[58.0-58.8]	[63.2-67.2]	[6.3-6.9]	[29.0-34.9]	[2.3-3.0]
100 : 10	[973-1,005]	[81.3-82.3]	[80.4-85.2]	[10.2-11.0]	[46.8-54.1]	[1.3-1.5]
150 : 15	[1,484-1,534]	[91.5-92.3]	[91.9-94.3]	[13.5-14.5]	[58.0-62.2]	[0.8-0.9]
200 : 20	[1,944-2,030]	[95.8-96.4]	[95.3-98.3]	[14.7-16.1]	[55.5-61.5]	[0.5-0.6]
250 : 25	[2,456-2,557]	[97.9-98.3]	[97.7-99.3]	[14.3-16.4]	[49.7-56.9]	[0.4-0.4]
300 : 30	[2,938-3,078]	[98.9-99.1]	[98.4-100.0]	[14.2-16.4]	[45.0-53.1]	[0.3-0.4]
350 : 35	[3,395-3,547]	[99.3-99.7]	[99.3-100.0]	[13.7-15.8]	[44.3-52.1]	[0.3-0.3]
400 : 40	[3,856-4,135]	[99.7-99.7]	[99.4-100.0]	[13.5-16.0]	[41.3-51.1]	[0.3-0.3]
500 : 50	[4,848-5,143]	[99.9-99.9]	[99.7-100.0]	[13.3-15.8]	[40.7-49.8]	[0.2-0.3]
600 : 60	[5,789-6,152]	[100.0-100.0]	[99.8-100.0]	[13.1-15.7]	[40.3-48.3]	[0.2-0.3]

density levels operatives couriered the messages around while at a higher density it was faster to transfer the message between operatives. These can be due to the environment being a fixed size, thus participants had increased likelihood to be within communication range of each other. The messages received increase along with their client coverage until the flooding of messages in the system causes it to slightly decrease. The random routing of messages floods the system, so along with the limited message buffer size causes messages to be dropped. The latency statistics support the operatives couriering messages at low density then taking less time as the density increased.

Our results show the effect of the increase in the number of participants on several metrics.

4.2 Number of Operatives to Clients Experiment

In this experiment we changed the number of operatives to service a fixed number of clients. As all messages need to pass through an operative to be delivered, having too few operatives creates a bottleneck. Increasing the number of operatives has a positive effect on the number of delivered message, latency and increasing the hop count. Highlighted in Table 4 we can see a peak in the number of hops to deliver a message at three hundred operatives. A reduction in operatives shows an increased tendency of messages to be held and physically transported around the environment, while increasing the number shows the increased dispersion between operatives increasing the probability of delivery in fewer hops. There is a diminishing rate of improvement in latency as the number of operatives increases, this indicates an increased probability of

Table 4: Operative to client ratio results.

Operative Client Count	Area Coverage %	Client Coverage %	Hops	Messages Received %	Latency (s)
50:20	[57.67-58.33]	[57.52-60.88]	[5.25-5.48]	[15.56-17.09]	[1.66-1.91]
100:20	[81.64-82.16]	[83.01-84.79]	[9.33-9.62]	[35.92-38.11]	[1.10-1.20]
150:20	[91.64-91.96]	[92.51-93.89]	[13.22-13.55]	[50.67-52.29]	[0.77-0.83]
200:20	[96.00-96.20]	[96.27-97.33]	[15.14-15.65]	[57.46-59.58]	[0.54-0.60]
250:20	[98.07-98.13]	[98.30-98.90]	[15.70-16.25]	[60.70-62.92]	[0.39-0.43]
300:20	**[98.97-99.03]**	**[99.10-99.50]**	**[15.75-16.30]**	**[64.77-67.05]**	**[0.32-0.35]**
350:20	[99.47-99.53]	[99.50-99.70]	[15.38-16.01]	[72.07-75.03]	[0.26-0.28]
400:20	[99.67-99.73]	[99.70-99.90]	[15.21-15.88]	[79.44-82.92]	[0.22-0.25]
450:20	[99.80-99.80]	[99.83-99.97]	[15.01-15.69]	[86.44-89.75]	[0.17-0.21]
500:20	[99.90-99.90]	[99.83-99.97]	[14.44-15.18]	[93.98-96.24]	[0.12-0.18]

an operative containing the message being within range of other operatives to transmit the message to and thus the client. Also as expected there is a positive relationship between the number of operatives and the percentage of successfully delivered messages, however there is not a predictable increase in improvement.

4.3 Effect of Message Density

This experiment changes the rate at which clients create new messages, thus changing the network load. As the number of messages increases, we would expect the system to become overloaded as the capacity to transfer messages is fixed.

The results in Table 5 show the expected increase in messages generated as the message density probability increases. As the load of messages increases, the hop count decreases, showing that as the number of messages in the system increases the operatives drop messages sooner. Interestingly, as the number of created messages flood the system, there is a decrease in the percentage messages received but at a slower rate of decline than the increase in number of messages.

Table 5: Message density results.

Message Density Per Second %	**Messages Generated**	**Hops**	**Messages Received %**	**Latency (s)**
0.5%	[1,485-1,506]	[16.37-16.96]	[78.52-80.88]	[0.28-0.31]
1.0%	[2,991-3,026]	[15.04-15.60]	[48.03-50.03]	[0.35-0.38]
2.0%	[6,001-6,043]	[13.46-13.87]	[28.99-30.06]	[0.37-0.39]
3.0%	[8,964-9,026]	[12.53-12.90]	[21.61-22.37]	[0.36-0.39]
4.0%	[11,921-11,991]	[11.81-12.18]	[17.63-18.34]	[0.35-0.37]
5.0%	[14,960-15,053]	[11.25-11.61]	[14.98-15.52]	[0.34-0.36]
10.0%	[29,943-30,028]	[9.47-9.83]	[9.22-9.65]	[0.29-0.31]

4.4 Discussion

Given the random positioning and movement initially defined for the operatives, changes in the experiment parameters give predictable results based on the current framework limitations. As the number of operatives increases so does the number of message routes, this increases the likelihood of a successful delivery.

Having an operative move around carrying a message is much slower than forwarding a message between multiple operatives to the destination client. Thus, as the network's area/client coverage increases the hop count increases while the latency decreases. Limiting the operative's communication rate and message buffer size leads to difficulties when the number of messages entering the system is increased past what it can successfully handle. As the number of messages entering the system increases, messages are more likely to be dropped by operatives before being delivered. The random nature of the operatives along with simple priority queues for message storage and forwarding gives promising results. We believe these results will only get better as the underlying methodologies on how the operatives behaves improve.

Once taking into account the client coverage (greater than 96%), increasing the number of operatives with respect to clients 200:20 to 500:20 also improved the performance of percentage of delivered messages ([57.46-59.58]% to [93.98-96.24]%) and latency ([0.54-0.60] to [0.12-0.18]). This improvement is due to the increased probability a route is found between the source and destination clients while the system is not being flooded by messages. Flooding of messages in the network is shown in the results as the number of messages sent [1,485-1,506] increases to [29,943-30,028]. Although the latency of the messages delivered remains around 0.2-0.3 seconds and the number of hops drops from for a set operative to client ratio of 300:30, there is a decrease in the percentage of messages received from [16.37-16.96] to [9.47-9.83] we can see the deterioration of the system as the number of successful messages delivered drops from [78.52-80.88]% to [9.22-9.65]%.

5 CONCLUSION

The Communication Collective is a potential solution to other forms of communications drawbacks, as it is made up from multiple mobile components it can avoid or mitigate existing problems: allowing redundancy, cost, moving away from danger or towards where it is needed and the ability to adjust its configuration.

With the increased computing performance, battery life, miniaturization, reduced power consumption and decrease in cost, the creation of a cost-effective adaptive communications platform is becoming a reality. However, achieving the desired system behavior as a result of the interactions between the system operatives is non-trivial.

For the initial creation of the Communication Collective simulation environment the system basics are working with participants being created, moving around the environment and creating/communicating messages. Initial statistics show inputs are affecting outputs in the expected manner. Our analysis finds that when client coverage is low [58.0-58.8]% the percentage of messages received is relatively low [29.0-34.9]%, with messages more likely to be physically transported by a moving operative to the client. As the client coverage increased [95.8-96.4]% while maintaining the same ratio of clients to operatives (10:1), we see an improvement of delivered messages [55.5-61.5]% with the messages passing through more operatives [14.7-16.1 hops] and dramatically reduced the latency [0.5-0.6 seconds]. These preliminary results show promise in the described Communication Collective as a concept and the initial basic implementation and how the basic implementation is letting the system down.

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