PRINCIPLES OF COGNITIVE NETWORK TEAMWORK

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ABSTRACT

This paper looks ahead at the future of wireless communications systems that can combine their resources and capabilities in order to enhance their overall ability to collect and convey information. Cognitive network teamwork has significant potential in the development of new public-safety, entertainment and military applications. Specifically, descriptions of the principles of formation, co-ordination and management of an effective cognitive network team, and an exploration of the key processes involved are presented. Also described in this paper are the different roles that an individual cognitive node can adopt within the team, how a cognitive network team can benefit from the rewards of successful teamwork, and how inevitable change in membership and network topology can be handled. Finally, a relevant example scenario is outlined in order to suggest a suitable context for these principles.

1. INTRODUCTION

A single individual may not have all of the required skills, knowledge and time required to solve a challenging problem. Humans work together in an attempt to solve a complex problem or series of problems in the form of a team or army. A team has the benefit of a shared pool of knowledge and expertise in order to potentially devise an effective (and a more timely) solution. Belbin [1] and Wheelan [2] describe the characteristics and dynamics of an effective team, and these principles can be applied in a wireless communications context in the form of a cognitive network. The characteristics of an effective team include team members with complementary skills, who share a well-defined common goal and have clear roles within the team. The evolutionary process of a team requires strong communication, co-ordination and conflict-resolution capabilities.

The overall objective of a cognitive network comprising two or more nodes with cognitive functionality is to facilitate and maintain the flow of information between one or more sources and one or more sinks. Each node in this wireless network may be constrained by the available energy, RF front-end characteristics, cognitive abilities, quality and diversity of available information, and other radio resources, geographical, frequency spectrum, and interference factors. As a consequence, an individual node may not have the capacity to form and implement an optimal (or near optimal) communications solution. The principles of cognitive radio can be applied to the network to avail of the individual knowledge, resources and individual cognitive abilities of each node in this network.

This paper describes the principles of formation, co-ordination and management of an effective cognitive network team and the processes involved. Also described in this paper are the different roles that an individual cognitive node can adopt within the team, how a cognitive network team can benefit from the rewards of successful teamwork, and how inevitable change in membership and network topology can be handled. Cognitive network teamwork has significant potential in the development of new public-safety, entertainment and military applications, therefore some relevant example scenarios are also outlined.

2. CO-OPERATION AND COLLABORATION

Collaboration is the process of two or more entities working together, or acting co-operatively in the pursuit of their own individual or shared goals. This co-operation can take the form of access to information, services or other resources that may not be available. Collaboration can take place in an intentional but also unintentional manner. Treasonable and parasitic co-operation activities are also forms of collaboration. In this case, both parties may not be aware of the intentional or unintentional collaboration, or may even have orthogonal objectives. However, the processes required by both entities to accomplish these orthogonal goals may involve common approaches. As distinct from active collaboration, passive collaboration can be viewed as providing a service or making information available, but other entities can take advantage of this without having to form an intentional relationship.

The topic of collaborative spectrum sensing [3] is one example of this behavior, where information from two or more nodes can be combined to form a better picture of how spectrum is used over a wider frequency, time or geographical space range than what a single node could achieve by itself.

3. TEAMWORK

Effective cognitive network teamwork involves a relatively small number of cognitive nodes with complementary cognitive and signal-processing abilities and radio resources, who share a common goal (or set of common goals), and who are accountable for their actions. The collective action of a cognitive network team can potentially surpass the abilities of an individual node within that network. Teamwork therefore represents a new evolutionary stage of cognitive radio and cognitive networks development.

Members of an effective team are not created equal in abilities, strengths, and indeed weaknesses. These team members generally have qualities that complement those of the rest of the team. As a result, team members can adopt different and necessary roles within the team according to their skills and strengths.

Fig.1 is an illustration of the differences in RF front-end capabilities, energy levels, and cognitive functionality that may exist between two cognitive radio nodes. Node A may have a wideband, frequency agile RF front-end, with a large TX power range, high receiver sensitivity and large dynamic range, for example. Node B on the other hand may not have such a high specification RF front-end. In addition, Node A does not have the high degree of cognitive functionality that Node B possesses. By combining these complementary abilities and working as a team, it is feasible that the potential of the team unit can surpass that of each entity operating independently.

This section also describes the roles that are common traits of highly effective teams. Wheelan [3] states that these roles can consist of either one, or a mix of, the four following categories:

- Diverger
- Assimilator
- Converger
- Accommodator

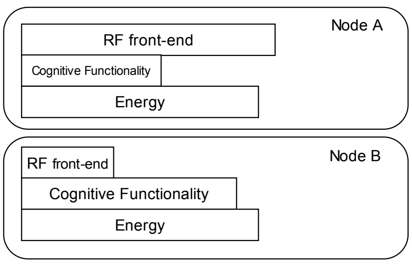

Fig. 1: Description of complementary abilities and resources where Node A has a better RF front-end than Node B but Node B has better cognitive functionality than Node A.

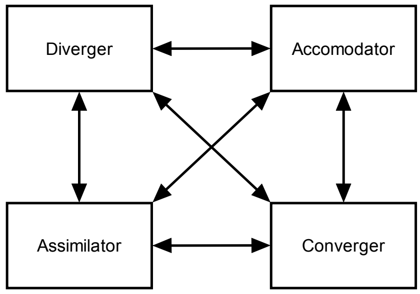

Fig. 2: The four key 'personalities' in an effective team (Diverger, Accomodator, Assimilator and Converger) rely on ability to freely exchange information with each other.

A *Diverger* is a team-player entity that is biased towards feelings and people. In a cognitive radio context, the diverger's strengths lie in maximizing the benefit for the network and individual devices, while maintaining a focus on self-preservation by aiming to maximize operating lifetimes.

The role of an *Assimilator* is one that is oriented towards rational thought and logical analysis of a scenario or problem. A cognitive radio with an enhanced decision-making and analysis abilities can be categorized in this role. An assimilator in this case could make use of internal and external observations, knowledge of previous outcomes and conclusions as part of the logical analysis process.

The third role is that of a *Converger,* which refers to an entity that is primarily oriented towards action and practical implementation. This entity converts the team-plan and viable conclusions into a set of actionable items. In a cognitive radio, the Converger node has a high degree of flexibility and reconfigurability, capable of coping quickly with change. This reconfiguration can be directed by the outcomes of the Assimilator, which produces the set of actionable items.

The final key role is the *Accommodator*. This entity is mainly oriented towards exploration of new techniques, hypotheses testing, and innovation. In a cognitive radio contest, an Accommodator can be viewed as the machine learning core of a cognitive radio. The main output of this entity is the development of new conclusions based on historical stimuli, recorded actions and conclusions from previous exploration and activities.

4. TEAM DEVELOPMENT

An effective team of cognitive nodes undergoes a number of distinct development stages, which may continue in a cycle during the lifetime of the entire team. It is difficult (if not impossible) to establish a team without some form of inter-node communications. These team-formation and co-ordination processes require communication between nodes in order to evolve.

Wheelan describes four stages of team development, which are illustrated in Fig. 3. These processes can be described in terms of cognitive radio nodes as follows:

Inclusion and Dependency (Forming)

The discovery and assembly of a core group of cognitive nodes is first required before a team can be established. Node discovery may take place using an advertising mechanism or selective invitations based on knowledge of past team behavior. Co-ordination at this stage may be largely governed by the node (group leader) that initiated the call to action.

Counterdependency and Conflict (Storming)

Following the initial formation stage, the establishment of a set of team goals and operational guidelines is required. One example of a team goal may involve the measurement of spectrum usage over a wide geographical area and dissemination of these measurements into two categories: occupied spectrum and 'white-space'. This process of goal-establishment may require further iterations in order to clarify ambiguous goals. An example of this may occur when nodes do not have specified measurement durations or frequency ranges. Conflict may arise when a group goal either contravenes the individual goal of a group member as may be the case when one node is required to transmit information for a user whereas the team goal is to sense the spectrum in receive-only mode during the same time-interval. Group members can attempt to position themselves in a role that is perceived to yield maximum benefit based on their current resources and cognitive reasoning capabilities. Conflict resolution mechanisms are therefore required in order to help the group to progress to the next stage of team development.

Trust and Structure (Norming)

During the *Norming* stage, trust relationships between the member nodes develop. With a clear and agreed set of goals, the focus of the group moves towards identifying the strategies, techniques and work practices required to attain the desired goals. The team becomes more defined as redundant or unwilling nodes are removed from the pool of available team players. Direct communications with the initial group leader begins to decrease, inter-node communications begins to increase, and the initial reliance on the guidance of the group leader diminishes.

Subgroups may emerge as the nodes in the newly-formed team identify common characteristics in the form of cognitive capabilities, available radio resources and ability or willingness to innovate. Each subgroup may then form specialist groups focused on tackling a specific area of the global task. An example of this specialist task may involve processing huge amounts of spectral data in an attempt to differentiate between occupied spectrum and 'white-space'.

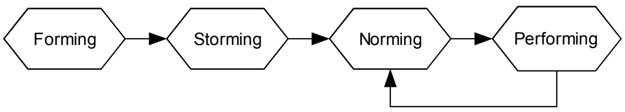

Fig. 3: Development path of a team.

Work and Productivity (Performing)

This stage is usually signaled when the team begins working on their individual or subgroup tasks. Each team member should have a clear idea of the team goals and what their individual roles within the team are. These assigned roles ideally match the skills and expertise of each member. The team itself contains the smallest number of members required to attain the desired goals and begins *Performing*. The team may be working for a reward for successful team-behavior outcomes. Team member intercommunications traffic is mainly in relation to team co-ordination, updates and constructive feedback traffic. This can take the form of status reports, emerging issues and suggested new approaches based on the outcomes of innovation and hypotheses tests.

One of main challenges of a cognitive network is dealing with the changing states of member nodes. The available energy, processing capabilities, locations and topologies, spectrum activity, wireless communication channel, and possible hardware malfunctions are some of the key factors that affect the ability of a member node to perform effectively or at all. It is a reasonable assumption that the team structure may change during the course of the exercise. To handle this change in a cognitive network team, three main approaches can be used.

No Action: The loss of a team member is accepted. Extra time may subsequently be required to accomplish the team goals due to this loss. It is feasible, however that the outcomes of the ongoing innovation processes may result in a more effective method in achieving the team goals(s) thus requiring less work. Therefore may mean that the loss of a team member does not have a significantly detrimental impact on the overall effectiveness of the team.

Reconfiguration: The other nodes in the network team may attempt to adjust their own tasks in order to share/absorb the role(s) of the expired or unresponsive team member. This requires an ability to detect the loss of a team member, establish what effect this may have on the team's attempts to accomplish its goals and co-ordinate activities so that the outstanding tasks can be accomplished.

Supplantation/Recruitment: An expired or unresponsive node is either supplanted or replaced by a new node. The team may evolve to the second or third stage of team development due to possible conflicts as existing team members re-adapt to the change in team structure. The process of integrating the new node into the team may trigger existing team members to re-evaluate their roles as individual node resources, locations, objectives and team goals may have changed significantly since the team-formation stage.

5. FACILITATING TEAMWORK IN A COGNITIVE NETWORK

There exists a set of necessary elements that must be enabled before the principles of effective teamwork can be realized in a practical cognitive network. The technological challenges include devising robust methods for discovering available and new potential team members, coordinating the actions of the group members, making decisions (where the required information and abilities to form and disperse the decision information may be separated in space and connected only by a wireless communications link), and delegation of tasks and implementation of an effective team solution. In addition, a method used to account for the actions of the distributed team acting as a single unit is also another important technological challenge.

The foundation and subsequent management of a practical cognitive network team therefore requires a combination of the following abilities and characteristics:

- Awareness
- Knowledge Representation
- Discovery
- Co-ordination
- Distributed Decision-Making
- Implementation
- Accountability

Awareness: A cognitive network team-player node should ideally have as much relevant and timely contextual information as possible available in order to make better strategic decisions regarding a particular scenario. This can include self-awareness information relating to the perceived abilities, energy, available RF front-ends, and other radio resources, and external information relating to the physical (including frequency spectrum), social, economic, and time domains.

Knowledge Representation: This refers to the ability to interpret, and make inferences, from one or more data sources. Data in this case can include the awareness information, actions and strategies, and conclusions and outcomes from derived from previous experiences. The challenge here is to implement a light-weight means of representing this knowledge in a machine-understandable format analogous to how humans perceive data as names, addresses, bank account numbers, a list of instructions, etc.

Discovery: In order to form a team, it is necessary to first discover who the potential team members are and find out where their strengths and weaknesses are, and to deduce what their ability and willingness to work as a team is. Cognitive radio nodes may have different levels of capabilities and available resources, which may be made available for use by the team. A passive (non-transmitting) node can be difficult to detect unless it responds (using a signaling/beaconing mechanism) to a query other nodes. Indication of node availability and advertisement of its cognitive and signal-processing capacity is yet another challenge that needs to be overcome in order to facilitate cognitive network team-formation and co-ordination.

Co-ordination: The formation of a team of cognitive nodes in a coherent and logical manner requires co-ordination. This co-ordination mechanism is not a non-trivial problem. The reason for this is that the nodes may be distributed over a geographical area, connected only by a tenuous wireless communications link, and the establishment of communications with these nodes is first required before co-ordination commands can be issued to influence the behavior of the nodes. Co-ordination may also involve nodes from other networks of cognitive radio nodes. In fact, this ability is required throughout the entire teamwork cycle (from the *Storming* to the *Performing* stages). As a result, it is important to enhance the robustness of a practical co-ordination and control implementation.

Distributed Decision-Making: A decision-making entity may have to consider information from many directly and indirectly-linked nodes in an ad hoc cognitive network. This information may arrive sporadically thus making the ability to form sound decisions even more difficult. To maintain an effective working team, this form of decision making must be biased towards the accomplishment of the common team goals and the maximization of the value and rewards for the team as a whole, rather than for a single node. The decision-making process also involves deciding whether an action or solution can be implemented by the device itself (local decision) or whether a cognitive network team approach may result in a more effective or timely solution (distributed decision).

Fewell [4] describes three classes of decision:

Reactive Decision: According to a pre-determined ruleset or a decision make quickly before a deadline expires. This quick decision may be sub-optimal.

Doctrinal Decision: Based on previous conclusions, outcomes, and successful tactics learned and developed over time.

Deviating Decision: The decision deviates from the established doctrine, which may be a novel and untested approach.

Effective decision-making also requires reliable information and an indication of the potential consequences of each decision. A portable and low-overhead means of knowledge representation is therefore vital for successful team behavior. It is feasible that all of the required information may not be available, may require excessive energy or processes to acquire, or there may not simply be enough time to collect and process this information. In this case, a fast and frugal heuristic approach may be employed, where a decision can be made using less effort and a reduced set of available knowledge at the expense of decision quality.

Implementation:

Decisions and conclusions are of limited value unless they can be applied. Each cognitive node must therefore be heteromorphic i.e. capable of changing its structure and parameters dynamically and quickly. Conventional ad hoc network traffic operates on a per-hop basis. Therefore there exists the possibility of an implementation and/or decision-diffusion time-lag across a wide network depending on the node degree of the network. This may present another challenge as decisions and the list of actions may only have a limited timespan in which to be implemented. One of the challenges in realizing this system is devising a distributed decision distribution and network-wide implementation technique that accounts for the possible time-lags due to network propagation times.

Accountability:

Accountability measures can help future cognitive network teams to learn from the outcomes of previous team behavior. Accounting for the actions and outcomes of team-behavior enables this team to learn. Therefore, following the completion of a cognitive network task, a means of reporting and distributing the results of the team action to the members is ideally required in order to help the team and team members develop.

6. EXAMPLE SCENARIO

In order to help indicate the potential of cognitive network teamwork, this section describes a spectrum monitoring scenario. A frequency spectrum map of a wide geographical area is required by a spectrum regulator. A domain of two hundred cognitive nodes currently exist within this area and have formed an ad hoc network. The regulator's cognitive radio device is not capable of undertaking this formidable task on its own so it needs help from a cognitive network team. The advertised reward for successful completion of the task is 10 free spectrum-usage credits for each member of the team. In addition, each participating node will benefit from the combined spectrum-usage information over this geographical area for its own operational purposes. Each node in the current network has a limited ability to sense spectral usage. The ability of each node to perform frequency spectrum measurements is one of the following cases:

- No ability to measure spectrum-usage.
- Narrow bandwidth, short duration measurements.
- Narrow bandwidth, long duration measurements.
- Wide bandwidth, short duration measurements.
- Wide bandwidth, long duration measurements.

The individual goal of each cognitive device in the network is to maximize the number of spectrum-usage credits in its store as well as gain more information about the frequency spectrum without significant effort on its part. Volunteer devices with spectrum sensing capabilities from all of the cases above register their interest in participating. Three cognitive devices with no ability to sense spectrum also register their interest because they have learned from previous activities that group tasks require significant message-passing between nodes. Therefore, although they cannot take part in the main activity, they can still participate in team operations thus qualifying for the team reward on the expected successful completion of the task.

7. CONCLUSIONS

This paper described the key principles of effective teamwork in a cognitive radio and network context. Common traits of an effective team were identified, following on to an outline of the key processes that a team progresses through in its development cycle. Certainly, a great deal of research challenges still remain before complex team processes can be realized in a cognitive network context. In this paper, an outline of these research challenges has also presented. Finally, to help illustrate the context in which these principles can be applied, a public-safety scenario involving teamwork to help provide an effective solution was outlined.

8. REFERENCES

[1] Belbin, R., *Team Roles At Work*, Butterworth Heinemann, ISBN: 0-7506-2675-5, 1993

[2] Wheelan, Susan, A., *Creating Effective Teams: A guide for members and leaders*, Sage Publications, 2nd Ed., ISBN: 1-4129-1376, 2005

[3] Ganesan, G.; Ye Li, "Cooperative spectrum sensing in cognitive radio networks," *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on* , vol., no.pp. 137- 143, 8-11 Nov. 2005

[4] Fewell, M.P., Hazen, M.G., 'Cognitive Issues in Modelling Network-Centric Command and Control', Defence Science and Technology Organisation (DSTO) System Sciences Laboratory, Department of Defence, Australian Government, May,2005.