RESEARCH ARTICLE OPEN ACCESS

Resource Dependent Radio Allocation For Battlefield Communications - A Data Model Approach

Gregor Thomeczek*, Ian Colwill*, Elias Stipidis*
*(Vetronics Research Centre, University of Brighton, UK)

ABSTRACT

Network Enabled Capability (NEC) and the Land Open Systems Architecture (LOSA) are novel approaches to enable interoperability between a heterogeneous collection of assets in the battlefield. These paradigms utilise an underlying network for cooperation between deployed battlefield equipment. NEC and LOSA have great potential to transform military communications and enhance integrated survivability as well as situational awareness, but the Achilles' heel of NEC and LOSA is the wireless spectrum over which they must communicate. A noisy and dynamic battlefield wireless spectrum as well as an array of heterogeneous wireless communications equipment handling multiple types of data with different Quality of Service (QoS) requirements requires a system which manages and allocates these communication resources effectively. This paper presents the High Availability Wireless Communications (HAWC) system, a hardware agnostic communications controller middleware to manage any combination of existing and future multiband wireless resources. The system utilises a vehicle's data model to gather information about available radio resources and enable LOSA by meeting communications data requirements and delivering appropriate QoS to the appropriate traffic in a fleet of vehicles. The functionality of the system is verified by using behavioural simulation on a virtual battlefield.

***Keywords* –** Data Model, Application Aware, Multiband, Vertical Handoff

I. INTRODUCTION

The field of Multi-Hop Ad-Hoc wireless networks, especially Mobile Ad-hoc Networks (MANET) is developing rapidly. MANETs are easy to integrate into existing infrastructures and fulfil a clear need for seamless information exchange and shared situational awareness for Network Enabled Capability (NEC) operations between military vehicles [1, 2]. However, wireless networks are unreliable due to a number of factors, such as fading channels and environmental attenuation, making widespread penetration of emergency and military services difficult [2-5].

In NEC warfare, with increasingly heterogeneous assets in the battlefield including specialised vehicles, both manned and unmanned, dismounted soldiers carrying advanced C4I technologies and multiple capability wireless communications [6, 7], a robust and reliable wireless communications network becomes essential [8]. In addition, the increased use of Commercial-Off-The-Shelf (COTS) components results in faster upgrade cycles, higher modularity and a need for management of an increasing range of heterogeneous communications infrastructure [9].

As Battlefield networks are under constant threat of attack, the need for high reliability and high availability is evident. Battlefield networks are comprised of a large number of mobile nodes, hence the network must be wireless and is required to provide a high level of QoS. However, tactical networks face a harsh environment; saturated radio bands, intentional interference and a hostile topology are only a few examples of factors that threaten communication and result in a highly dynamic pattern of availability.

In an NEC environment, multiple heterogeneous radio technologies are employed for battlefield networks. Using these multiple technologies simultaneously provides an added layer of redundancy for high priority data and enables the source to communicate with many neighbours simultaneously [10, 11]. Redundant wireless communication can reduce latency, as well as increase availability of radio links, however, a balance must be achieved between contrasting QoS requirements.

II. RELATED WORK

Several promising studies have been performed involving communication networks with multiple heterogeneous wireless interfaces. Yoon et al. show a significant improvement when using a secondary higher range, lower throughput wireless interface to fall back on when the primary high throughput, low range interface fails [12]. Qi et al. propose a handoff scheme which takes into account user preferences and traffic types by using Group Decision Making

(GDM) to consolidate two Multiple Attribute Decision Making (MADM) parameters based on objective and subjective decision making processes [13]. In another paper rather than using MADM Qi et al. focus on optimising network throughput by using Markov chain parameters to perform the network and handoff target selection [14]. Ma et al. use an Analytic Hierarchy Process (AHP) for the calculation of multiple QoS parameters evaluated by Simple Additive Weighting (SAW) and Grey Relational Analysis (GRA) for the calculation of the radio weighting in a MADM algorithm [15]. Chamodrakas et al. propose a method that selects a network to balance performance and energy consumption by weighting metrics such as user preference, bandwidth, delay and energy consumption with a TOPSIS algorithm. Fuzzy logic is used to avoid conflicts of inconsistent ranking parameters. Yonghoon et al. investigate multi-radio access networks where a node is permitted to transmit data over multiple wireless interfaces simultaneously and concludes that parallel multi-radio access is superior to switched multi-radio access [16].

III. LOSA AND THE DATA MODEL APPROACH

The data model approach is a paradigm currently under development by the UK MOD in an effort to manage the ever increasing complexity of military vehicles. Increasing modularity facilitates COTS replaceability in case of damage as well as upgradability, but also means that an increasing number of discrete systems must be able to communicate with each other within a vehicle.

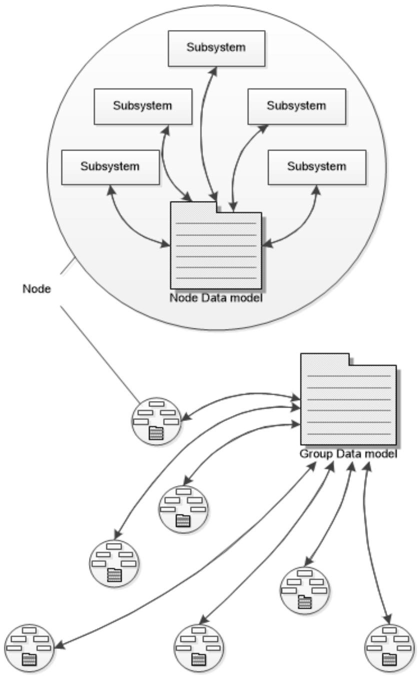

Figure 1:Data Model, Node Level vs. Group Level

Using a data model approach, subsystems are able to publish and subscribe to information maintained on a shared data model. Data models are planned at an individual platform (hereafter referred to as node) and group level. At the node level this makes it possible for each subsystem to access a wide range of data simply by subscribing to it. For example a communications controller on a vehicle with a number of wireless transceivers and access to the rest of its vehicle platform will subscribe to topics, such as *radio.throughput*, *radio.range*, as well as nav.*location* or nav.*velocity*. Upon reception of the subscribe request, each radio is required to publish up-to-date information about itself depending on the mode of subscription agreed upon.

Through LOSA, the data model concept is being expanded to a fleet wide, system of systems level (see Fig. 1), enabling platforms to publish and subscribe to topics of other vehicles and even their subsystems. Thus if one vehicle's communications controller needs to know its neighbour vehicle's location, it simply subscribes to a topic like *vehicle(i).nav.location*. This way a whole fleet can be more interconnected, information sharing vital for situational awareness is facilitated and interoperability is enhanced.

Many radio resource management algorithms exist in the literature, the common factor between them being that they need performance metrics to base any decision on. With the data model approach it is possible to acquire up-to-date metrics in a straight forward manner simply by subscribing to them.

IV. HETEROGENEOUS HARDWARE

A diverse collection of assets, all with unique sets of communications hardware can be observed in the battlefield. It is imperative that any communications controller attempting to manage these diverse radio technologies is compatible with a wide range of radio equipment as possible. We propose a novel method to facilitate upgradability and compatibility with future, yet unknown equipment by defining a clear set of interfaces with which the controller interacts with any attached transceivers providing any future equipment adheres to the same basic interface specification [17].

Through the nature of COTS and the role the UK MOD plays as a customer, it is assumed, that communications equipment designed to interface with any future vehicular system will adhere to military specifications, such as the ability to run data models, data distribution services, etc., as well as providing interfaces to send and receive data and report performance. Generic interfaces allow the controller to utilise potentially any underlying communications technology, i.e. Satellite, radio, optical etc., for simplicity we will use radio transceivers in this paper.

To address the challenges that arise with the employment of dynamic nodes and a dynamic environment, a next generation communications controller can utilise the data available from a node's data model to effectively interface a variety of transceivers with the appropriate traffic.

V. HIGH AVAILABILITY WIRELESS COMMUNICATIONS

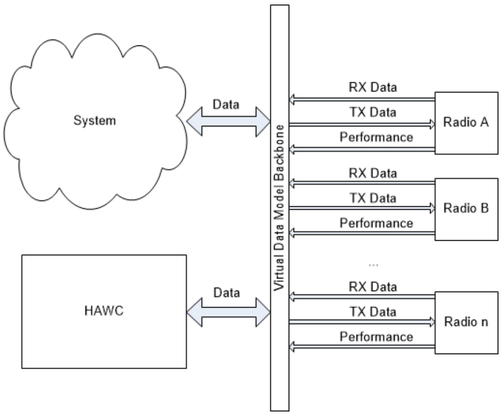

Figure 2: HAWC System Diagram

A scheme is proposed whereby HAWC acts as a mediator between communications traffic and the attached radios. The controller interrogates any available radio as to its type and performance; hence each type of transceiver can be distilled down to its basic performance principles and then treated according to those merits. Each radio is evaluated and assigned traffic based on how well it fulfils the requirements of a given type of traffic.

HAWC is connected to the same virtual data model backbone as all attached radios and the rest of the system (see Fig. 2). All radio equipment will publish land data model topics. The HAWC controller will monitor the radio's typical performance in terms of these parameters:

5.1 HAWC profile QoS parameters:

- Range
- Throughput
- Latency
- Jitter
- Packet Delivery Ratio (PDR)
- Signal to Noise Ratio (SNR)
- Frequency Band
- Safety level
- Security level
- TX Current consumption
- RX Current consumption

5.2 HAWC profile QoS requirement parameters:

- Required bandwidth
- Time criticality
- Safety level
- Security level

While in operation, the transceiver continuously evaluates its own performance and periodically reports these updated performance metrics to the data model for processing by the HAWC controller. The system starts off with an approximation of each transceiver's capabilities which become increasingly refined as time progresses. This is necessary to take into account variations in the system's environment, such as noise on the spectrum, weather, foliage, terrain and others. Particularly in case of battle damage, the HAWC controller must recognise the damaged component and treat it as deprecated depending on the effect of damage it has received. When the damaged transceiver is swapped for a new unit, the unit will update its data model topics and the HAWC communications controller should re-evaluate its communication performance profile taking the reinstated resource into account. Similarly when a transceiver is replaced with a newer model with improved performance, the controller must recognise the improved resource available and re-evaluate the communication performance profile accordingly in order to make the most use of its enhanced capability.

Whereas many Generic Link Layers seek to obscure and hide the individual communication channels from the node controller (or user), the proposed system is aware of the communication link's properties and chooses a channel suited to meet a specific type of communication data requirements. Given prevailing conditions, it is possible to match data with a certain QoS profile to a suitable wireless interface and take advantage of each radio's specific qualities.

VI. HETEROGENEOUS TRAFFIC

Inter platform communication consists of a number of different types of traffic, requiring varying Quality of Service (QoS). It is therefore often imperative to transmit this data according to its requirements, i.e. to transmit high criticality data via a high safety level connection and prioritise it before low criticality, best effort data. Knowledge of a node's wireless communication capabilities, including how many radios are available as well as QoS on these devices enables the node to control over which channels data is being transmitted in order to maximise the node's communications utility, whilst maintaining QoS levels.

VII. RESOURCE ALLOCATION AND MODULARITY

Matching of the communications data with the available radios can be achieved by building profiles of both the data to be transmitted and the available radio transmitters. The proposed system functions as a broker between traffic and radio. Requirements and resources are compared and matched in terms of radio capability and data QoS requirements.

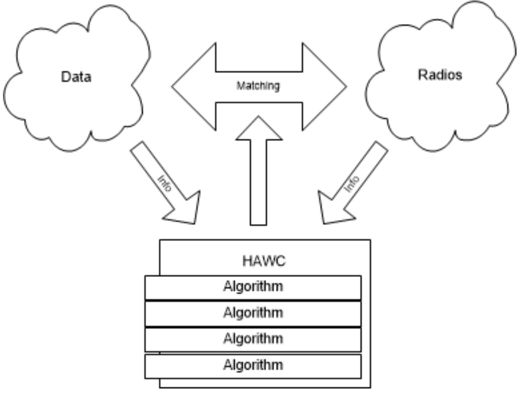

Figure 3: HAWC as a Broker

HAWC implements radio allocation by using suitable algorithms evaluating each radio's metrics (see Fig. 3). It is clear from the related work that novel, improved resource management algorithms are being developed regularly, therefore in order to continue to remain at the state of the art, any communications controller must be modular enough to accept new algorithms when they become available.

Due to the requirements for modularity and upgradability at low integration cost, assuming HAWC compliance, the broker algorithms are modular and can be interchanged. When a more effective algorithm is available, it simply plugs into the system in place of the deprecated one.

The radios are treated as black box entities. Underlying changes in routing, clustering, etc. are left to the individual radio units and interpreted via the reflected performance in the HAWC profile. Communications data is then assigned to each radio based on performance rather than the method of achieving that performance.

VIII. BEHAVIOURAL *SIMULATION* OF NEC SCENARIO

A steady-state, agent based simulation is developed in java to model each node as an agent within its environment. By abstracting the algorithms into behaviour contained within each agent, they are free to move in 2D virtual space and communicate with other agents based on the algorithms to be simulated.

Behavioural simulation has a number of advantages. In addition to scalability, the simulation can be changed rapidly due to typically shorter development cycles allowing simulations of complex scenarios beyond the scope of a low level simulation [18].

Agent based simulation is well suited to this study in particular, as once an agent has been created and given the appropriate behaviour of a node, it can be replicated many times in order to simulate an NEC scenario with multiple vehicles traversing a battlefield as individuals interacting with one another.

8.1 Environment modelling and radio setup

To simulate a realistic NEC scenario, 50 mobile nodes are placed in a simulated battlefield measuring $1km^2$ and given behaviour to move according to a random waypoint mobility model with no pause time and a speed of 1m/s (see Fig. 4). The problems associated with the random waypoint mobility model, specifically the decaying average speed problems [19] do not apply in this case since the node speed is always a positive, nonzero constant.

Since this study deals with multi-technology radio communications, all nodes were equipped with the capability of transmitting and receiving data using two separate wireless communication links simultaneously. Each radio is modelled to use its own non overlapping frequency band.

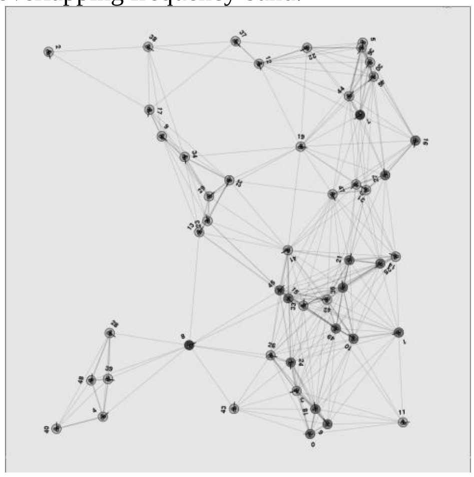

Figure 4: Mobile Nodes in a Simulated Battlefield

The primary radio is modelled on an 802.11a, 5GHz transceiver with a typical range of 120m and a basic data rate of 25Mbps. The secondary radio is modelled on an 802.11b 2.4 GHz transceiver with a typical range of 250m and a basic data rate of 5Mbps. Both transceivers use the loop free distance vector routing protocol BABEL [20]. It is assumed that "HELLO" and "I heard you" (IHU) messages are sent periodically and therefore all nodes are aware of their neighbours and neighbour tables are up to date.

To verify the HAWC system, multiple experiments have been carried out. These experiments simulate partial damage to the network to show how HAWC can be used within a dynamic battlefield environment. To illustrate typical performance of the network, the first experiment shows Packet Reception Ratio (PRR) over time with and without damage and the effects of using HAWC. The experiment is then repeated ten times in order to establish a trend in the results. Finally, the effect of damage on traffic allocation on a node level is investigated in more detail.

8.2 HAWC

To show how the HAWC Controller can increase a node's communication utility by exploiting information gathered through the GVA data model [17], HAWC is running a Multiplicative Exponent Weighting (MEW) cost / benefit algorithm [21] to assign traffic to an appropriate wireless link *n* based on the product of the communications metrics x_n weighted by the exponents w_n. (1) describes the MEW Cost / Benefit algorithm:

$$Benefit = \prod_{n=1}^{N} x_n^{w_n} \tag{1}$$

To be effective, the HAWC Controller must have access to several kinds of information. As detailed in the HAWC profile QoS parameters, there are many metrics which can be used to classify communications data and wireless links. In this case the three transceiver metrics x_1, x_2, x_3 are throughput, SNR and PDR.

Under normal circumstances the MEW Cost / Benefit algorithm will always select the radio with the highest throughput first. When a link degrades due to the destination moving out of range, the controller selects another radio available to it in order to restore communications. If however a radio exhibits an unusually low SNR or PDR, the cost of using this radio increases and it is therefore no longer as attractive compared to the low throughput alternative. For example, if radio A and radio B have an available throughput of 2Mbps and 1Mbps respectively, radio A would be chosen for the next transmission unless Radio B has a PDR more than twice that of Radio A.

It is important to note that the focus of this experiment is not the cost / benefit algorithm. The algorithms inside HAWC are interchangeable, in this example an algorithm is used as a placeholder to showcase how HAWC benefits by taking advantage of the GVA data model to gain up to date information about its resources. Other handoff algorithms are available [21] and more effective algorithms are likely to be developed in the future. HAWC accounts for this through modularity.

8.3 Failover Algorithm

HAWC is compared to a failover algorithm similar to [12]. This algorithm will therefore always select for the highest throughput radio whenever available and fail over to a lower throughput, higher range radio when the primary link is broken. The failover algorithm does not take advantage of performance data about its radio resources, therefore if the primary radio only becomes partially damaged, while it may suffer from intermittent connectivity or high error rate, the failover algorithm will still select it.

Once a radio has been selected by either algorithm, this radio will select a next hop based on its individual range and routing algorithm.

The following experiments show how identifying this damage and applying a weighting factor to the radio’s transmission cost improves performance of the overall network by utilising intact radios where possible.

As nodes do not have a pre-set pattern of movement, a feasible route cannot always be established between source and sink, hence they are not constantly within connection range and some packets are therefore dropped. Packet collision and routing errors arising from nodes moving in and out of connection range also cause packet loss.

8.4 Experiment 1: Effects of damage and mitigation

In this experiment we consider the impact of battle damage to radio transceiving equipment. In theatre, radio equipment is typically damaged or impaired in the following ways:

- Damage to antenna – reduces PDR, SNR and range, increases error rate.
- Damage to transceiver unit – diables the unit.
- Jamming on specific frequency – reduces PDR and SNR

With mutliple radios available to each node, the implemented algorithm evaluates each radios SNR and PDR and weighs it against throughput, hence an intact radio with lower performance is chosen over a significantly impaired radio with higher stock performance. This differs to the behaviour of a failover algorithm which will attempt to use a damaged or intermittent radio provided it is in range to the target node.

A single source and sink are chosen. A 1Mbps data stream is transmitted from source to sink through the network. The simulation time is 5000 seconds and the simulation is run for three scenarios using an identical seed (the basis for the simulation’s random number generator) each time. The three scenarios are:

- Failover, no damage: all radios are intact, when the primary radio loses connection it fails over to the secondary radio.
- Failover with damage: 10 nodes in the network sustain damage to their primary radio transceives causing a 90% decrease in signal to noise ratio in these radios. Nodes use the failover algorithm and behave like in scenario 1).
- HAWC with damage: the same 10 nodes sustain damage resulting in the same 90% signal to noise ratio loss to those radios. HAWC allows the cost/benefit algorithm to access data metrics such as SNR and PDR in order to favour the intact secondary radios over the impaired primary radios.

Fig. 5 shows a timeplot comparing the packet reception ratio of all three simulation run demonstrating the extreme time-variability and unpredictability of the wireless spectrum. The experiements show that:

1) Varying PRR in the first run with no damage is mostly a function of node movement and broken routes as a result, as well as temporary high hop count reducing the overall throughput to less than 1Mbps, thus decreasing PRR.

2) With a much lower packet reception ratio resulting from a proportion of the primary radios in the network being damaged, PRR in the second run with damaged nodes using failover varies greately, sometimes reaching 1 when packets are routed along a low hop count path containing no damaged nodes, sometimes the connection drops out completely due to the failover algorithm selecting severely impaired radios which produce an error rate too high for successful communication.

3) In the third run HAWC susbcribes to data from the GVA Data Model in order to assess the current performance of each resource available to it. HAWC continuously selects the radio with the best performancce under varying condions of damage and failure. Because of the secondary tranceiver’s reduced data rate, the overall throughput is not identical to the first run, but the algorithm is able to mitigate most of the damage. At times the PRR is higher than that of scenario 1). This suggest that selecting the secondary, longer range radio is sometimes more beneficial regardless of damage to the primary radio and routing can be optimised further.

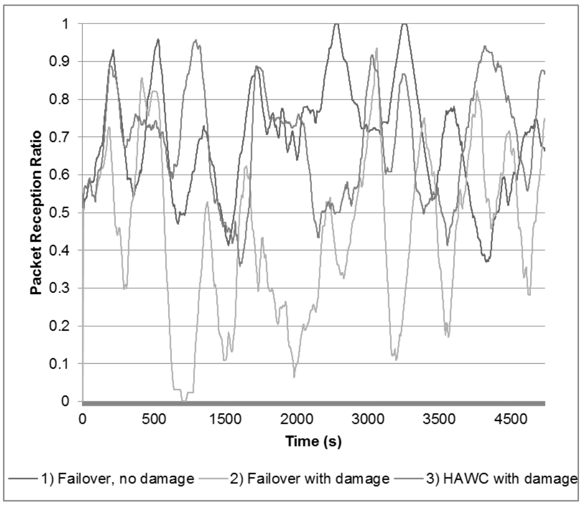

Figure 5: PRR Timeplot

To further examine the results of this simulation and to establish a trend, the experiment was run ten times, each time with a different simulation seed. For each run, node location and path is random.

Fig. 6 shows the results of these simulations and how the damaged radios significantly impact the overall PRR of the network with a 95% confidence interval.

The mean PRR for the failover algorithm with all nodes intact is 0.64. This PRR falls to an average of 0.38 when the damage is applied, hence, damage to random nodes in the network results in a mean 0.25, or 40% loss of PRR with a standard deviation of 0.07 across all ten runs.

The effect which damaged nodes have on the network and hence the loss in PRR varies from run to run. The reason for this variation is that the ten damaged nodes are not always on the routing path between source and sink, in some scenarios data packets have to be routed through damaged nodes much more often than in others, hence every damaged node has more significant negative impact on the network’s overall PRR.

By utilising information gathered via the GVA data model, the HAWC system is able to increase the network’s PRR back to an average of 0.62 over all simulation runs. This improvement also varies across runs. In particular run 5 and run 8 exhibit a higher PRR using HAWC and damage nodes than during the failover scenario without damaged nodes. This suggests that in some cases, using the secondary communication link with higher range and lower bandwidth is more desirable than always defaulting to the higher bandwidth, low range link.

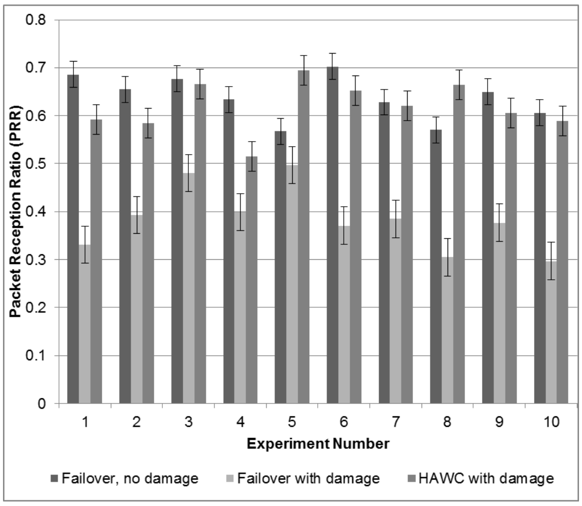

Figure 6: PRR Across Multiple Scenarios

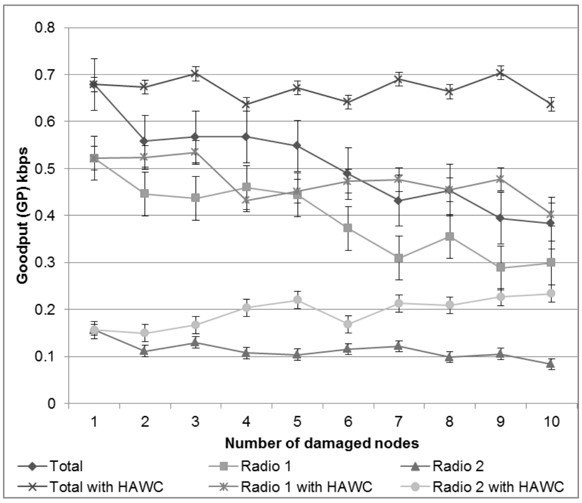

Figure 7: Individual Radio Performance

8.5 Experiment 2: Impact of damaged radios.

To further investigate the effect of an algorithm selecting damaged nodes, experiment 1 of the previous set was run ten times with a constant simulation seed and a variable number of damaged nodes in the network. The experiment was set up so that the number of damaged nodes increased by 1 each run, from no damaged nodes to 10 damaged nodes. Each run, a single additional node was damaged in a way that it suffered a loss of 90% SNR to its primary radio. The experiment was performed using both the failover algorithm as well as the HAWC system. The experiment measures goodput (GP) from source to sink, i.e. the useful throughput of the network disregarding protocol overhead and retransmitted packets. GP helps to visualise the performance of each radio transceiver separately, compared to the overall performance of the network in order to analyse the effect of damaged nodes in the network. Fig. 7 shows the results of this experiment with a 95% confidence interval.

As expected the number of damaged nodes is inversely proportional to the overall GP. When using the failover algorithm with an increasing number of damaged primary radios, the overall GP of primary transceivers in the network decreases by 43% from 522kbps to 299kbps, while secondary GP remains approximately constant at 114kbps. This causes an overall decrease in PRR of 43% from 679kbps to 384kbps.

When using the HAWC system, primary GP decreases by only 23% from 522kbps to 402kbps. Impaired radios are selected less frequently while secondary GP increases by 49% from 157kbps to 234kbps mitigating some of the impact of the impaired primary transceivers, keeping overall GP approximately constant at 670kbps.

IX. CONCLUSIONS:

In an effort for increased interoperability through fleet wide information sharing by using interconnected systems, emerging “System of Systems” technologies in military vehicles, such as LOSA and GVA rely on seamless communication within the fleet.

With a variety of traffic types with varying QoS requirements, as well as communication systems and transceivers with diverse capabilities, it becomes necessary to employ a system which manages a vehicle’s communication capability to match traffic with appropriate transceiver’s capability. Such a system will interface with COTS equipment in order to meet the military’s needs for replaceability, upgradability and interoperability, making the system compatible with a variety of transceivers.

The HAWC controller accepts new or interchanged hardware and the data model approach enables the system to assess the equipment. The proposed approach is scalable and works with multiple transceivers. Assessing any new hardware by its basic metrics enables the communications controller to compare radio transceivers based on their performance. The system treats transceivers as black boxes and does not interfere with their routing operations, but works as a broker between traffic and transceiver. HAWC manages dynamic environments, dynamic hardware and dynamic network traffic with zero user input and transparent upgrading and hardware adaption maximising optimum operation with reduced resources.

The HAWC approach has been verified by using a cost/benefit algorithm to address the effect of impaired radio transceivers for vehicle platforms with multiband capabilities. The proposed system has been simulated against a failover algorithm using 50 mobile nodes using a random waypoint mobility model with agent based behaviour in an NEC environment. The simulation compared control data to a scenario where a number of nodes' primary radio transceivers had been damaged and another scenario where the HAWC system mitigates the effect of the damaged radios. The simulation has been run multiple times in order to establish a clear trend in the simulation results and ensure consistency.

On average damaged nodes reduced the network's overall PRR by 40%, however HAWC, using data gathered from the GVA data model, is able to reallocate resources in order to restore 97% of the network's original PRR. Using HAWC, not only are the damaged radios utilised less, but the intact secondary transceivers mitigate most of the damage.

By using SNR and PDR to measure damage as an example it was shown how information about the radio gathered through the HAWC system and the GVA data model can be utilised to aid communications effectiveness.

Through the paradigms of GVA and LOSA a communications controller is potentially able to exploit fleet wide information to augment its functionality as a broker between communications data and radio resources. The system's modularity facilitates the use of future better algorithms to perform this exploitation.

In addition to quantitative improvements in performance there are significant qualitative advantages to HAWC. The modular, plug and play structure of HAWC provides significantly increased flexibility in all stages of a vehicle's life cycle. In the short term it facilitates rapid replacement and reconfigurability based on mission parameters or damage. In the medium and long term, the approach allows the vehicle to be rerolled, changing it from one purpose to another or upgraded with improved equipment.

X. FUTURE WORK:

In reality there are many different types of NEC traffic with highly variable requirements and characteristics as well as highly variable environment conditions which when taken into account would likely amplify the results of these experiments. With multiple transceivers already available to each node, data packets could be transmitted redundantly and simultaneously. Using redundant transmission techniques to achieve the level of reliability required in military operations results in a high bandwidth overhead, since work is essentially replicated most of the time. For some types of traffic, however, it may be worthwhile to divert resources to increase the chances of successful delivery. A system is needed to intelligently reassign network resources and to use existing resources on a vehicle platform more effectively taking into account all of these factors.

It is important to analyse how traffic characteristics and requirements can be mapped to existing hardware capabilities using a system of systems NEC approach. Therefore, it is necessary to research these existing capabilities and how they can be leveraged more effectively by managing communications traffic more intelligently in an effort to approach deterministic battlefield data transmission.

References

[1] K. Lund, A.E., D. Hadzic, T. Hafsoe, F. T. Jonsen, "*Using Web Services to Realize Service Oriended Architecture in Military Communication Networks*" IEEE Communications Magazine, 2007. 45(10).

[2] Z. Ye, S.V. Krishnamurthy, S.K. Tripathi, "*A framework for reliable routing in mobile ad hoc networks*", INFOCOM 2003. p. 270-280.

[3] J. Zhao, R. Govindan, "*Understanding packet delivery performance in dense wireless sensor networks*", Proceedings of the 1st international conference on Embedded networked sensor systems 2003, ACM: Los Angeles, California, USA. p. 1-13

[4] E. Ngai et al., "*A delay-aware reliable event reporting framework for wireless sensor-actuator networks*", Ad Hoc Networks, 2010. 8(7): p. 694-707.

[5] J. Shanshan, "*Optimal Wireless Network Restoration under Jamming Attack*". 2009.

[6] Rheinmetall-AG. "*Bundeswehr fields new Gladius soldier system*." 2013 27/02/2013; Available from: http://www.rheinmetall-defence.com.

[7] "*FIST - Future Infantry Soldier Technology*", United Kingdom. 2012 Available from: http://www.army-technology.com/projects/fist/

[8] NATO, R.a.T.O., "*IST-083 Technical Evaluation Report"*, 2008.

[9] D. McKinney, "*Impact of Commercial Off-The-Shelf (COTS) Software and Technology on Systems Engineering*", 2001.

[10] M. Kodialam and T. Nandagopal, "*Characterizing the capacity region in multi-radio multi-channel wireless mesh networks*", Mobile computing and networking2005, ACM: Cologne, Germany. p. 73-87.

[11] O. Younis, A. McAuley, K. Manousakis, D. Shallcross, K. Sinkar, K. Chang, K. Young, C. Graff, M. Patel, U.S. Army CERDEC, "*Cognitive Tactical Network Models*", IEEE Communications Magazine, 2010. 48(10).

[12] W. Yoon, N. Vaidya, "*Routing exploiting multiple heterogeneous wireless interfaces: A TCP performance study*", Computer Communications, 2010. 33(1): p. 23-34.
[13] Z. Shi, Q. Zhu, "*Network selection based on multiple attribute decision making and group decision making for heterogeneous wireless networks*", The Journal of China Universities of Posts and Telecommunications, 2012. 19(5): p. 92-114.
[14] Z. Shi, Q. Zhu, "*Performance analysis and optimization based on markov process for heterogeneous wireless networks*", Journal of Electronics & Information Technology, 2012. 34(9): p. 2224–2229.
[15] F. Ma, G. Xu, F. Yang, "*Capability adaptation algorithm based on joint network and terminal selection in heterogeneous networks*", The Journal of China Universities of Posts and Telecommunications, 2011. 18, Supplement 1(0): p. 76-82.
[16] C. Yonghoon, et al., "*Joint Resource Allocation for Parallel Multi-Radio Access in Heterogeneous Wireless Networks*", IEEE Wireless Communications, 2010. 9(11): p. 3324-3329.
[17] "*MOD, Defence Standard 23-09",* Generic Vehicle Architecture (GVA) 2010.
[18] R. Sinha, V. Christiaan J.J. Paredis, P. K. Khosla, "*Modeling and Simulation Methods for Design of Engineering Systems*", 2001.
[19] Y. Jungkeun, L. Mingyan, B. Noble. "*Random waypoint considered harmful*", INFOCOM 2003. 2003.
[20] J. Chroboczek, "*The Babel Routing Protocol*", 2011.
[21] E. Stevens-Navarro, V.W.S. Wong. "*Comparison between Vertical Handoff Decision Algorithms for Heterogeneous Wireless Networks*", Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd. 2006.