Designing

Tactical Networks –

Perspectives from a Practitioner

ABSTRACT

In today's network-centric battlefield, self-forming or self-healing networks play an important role in the operation of mobile forces that are deployed quickly to meet tactical demands. However, tactical network environments also pose significant challenges as a result of unreliable connectivity, limited bandwidth and latency issues. Research has focused on aspects including data link layers, routing and transport protocol as well as cross-layer optimisation. Many armies have large numbers of Very High Frequency and Ultra High Frequency narrowband tactical radios. The performance of these legacy radios can be optimised to support battlefield digitisation. This article suggests some guiding principles and key considerations in the design and implementation of tactical legacy radio networks for the Singapore Armed Forces.

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INTRODUCTION

Tactical networking facilitates information sharing and data exchange among military tactical force units to enhance operational processes and situational awareness. It enables command and control (C2) capabilities for network-centric warfare (Alberts, Garstka and Stein, 1999) as well as network-based defence (Lundqvist, 2000). The variations in tactical communication network capabilities are dependent on factors such as operational mobility, terrain, communication media resources and network characteristics. To facilitate interaction and interoperability at different tactical data networking levels, suitable adaptation at application level and network configurations need to be considered for deployment depending on the operational environment and resources available.

Mobile ad hoc networking is seen as a key enabler in realising the tenets of network-centric warfare at the tactical networking level. While current research and investigative work focus primarily on routing and transport protocol as well as wideband radio waveforms, there is still scope for a mobile ad hoc network over a legacy radio network. This is because many armed forces still have a sizeable number of narrowband radios operating at Very High Frequency (VHF) or Ultra High Frequency (UHF).

The tactical communication network can be designed to achieve effective data communication and exchange. There is a need for a structured approach that comes with a clear understanding of the operating environment characteristics, communication media limitations and application data exchange profiles. These form the basic tactical network design considerations to define the relevant network parameters and values. The tactical network design is then verified through simulation.

The main objective of this article is to present a practitioner's perspective on the guiding principles and key considerations for the design and configuration of tactical networks. The article also discusses possible challenges of adaptation for application implementation, as well as the proposed implementation of the various best practices for tactical C2 systems.

TACTICAL OPERATING ENVIRONMENT

There is a need to understand the tactical operating environment in order to appreciate its characteristics in deploying robust communication networks. Current tactical communication networks support VHF/UHF line-of-sight (LOS) waveforms as well as communication media e.g. Local Area Networks and Wide Area Networks. The key challenge lies in addressing typical tactical communication network constraints such as limited bandwidth and latency, narrow effective communication range, intermittent communication links, and potential hidden nodes in certain operational terrains. In addition, the mobility of tactical nodes causes rapid changes in network topology with the nodes leaving and joining the network on an ad hoc basis.

A tactical network is usually required to interact with a static strategic network which has a larger bandwidth and more reliable communication links. Data exchange across different network levels is required to support tasking to subordinate tactical-level force units, and to allow reporting on-the-ground battlefield status to higher command.

Limited Bandwidth and Latency

The bandwidth of a tactical communication network is dependent on what the communication media can support. If the most stringent communication media is adopted, there is a need to ensure that the network configuration is able to support VHF/UHF radios with low data rate. It is important to analyse the user's data sending requirements to address the problem of limited bandwidth. Pre-formatted data messages should be used to streamline data exchange and reduce overheads. Messages of large data sizes must not be sent to avoid overloading the network and increasing network latency. The number of nodes per network configuration should also be assessed, as more nodes will increase the network data traffic and latency.

Intermittent Communication Links

Due to the high mobility of tactical nodes, communication links may be broken due to terrain masking. Thus, networked nodes may appear online and offline intermittently, indicating that the communication links are unstable and unreliable.

This issue needs to be addressed at the routing protocol and application layers. Routing requires mechanisms such as 'store-and-forward' to enable data to be stored at one of the networked nodes within proximity of the destination node. When the destination node is back online, data will be forwarded to it. This 'store-and-forward' feature saves network bandwidth as the sender node will not have to re-send the data to the destination node. At the application end, data buffering needs to be managed to avoid buffer overflow, while the data size transmitted should be small to ensure better success of receipt.

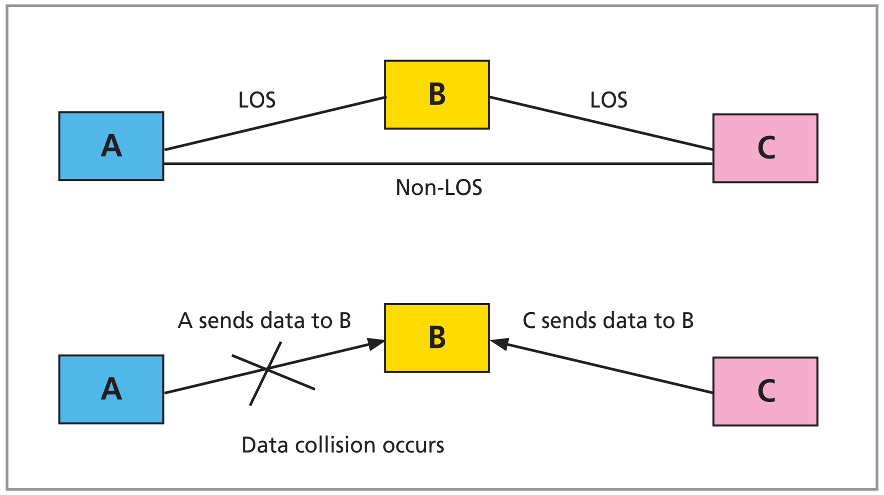

Figure 1. A hidden node scenario

Hidden Nodes

The hidden node phenomenon is usually caused by the absence of the LOS between some networked nodes, which may be due to mobility, terrain masking or weak signal strength. Figure 1 illustrates a scenario where networked node B is within LOS of nodes A and C, whereas node A is out of LOS of node C. When node C transmits data, node B will be able to relay this information via carrier sensing while it withholds data transmission from itself to avoid data collision. However, as node A is out of LOS of node C, it is unable to perform carrier sensing for any data transmission from node C. Thus, data collision may occur if node A has data to send.

For LOS radio networks, there are several variants of Medium Access Control (MAC) schemes such as Carrier Sense Multiplexing Access (CSMA) and Time Division Multiplexing Access (TDMA). The selection of the appropriate MAC scheme is critical to ensure a successful adaptation to the operating environment.

CSMA is a distributed random access protocol that is based on random carrier sensing before the initiation of any data transmission. It is also sensitive to the hidden node phenomenon. Literature reveals several variants of CSMA implementation that attempt to overcome the hidden node problem. Collision avoidance mechanisms such as using the random carrier sensing timer before data transmission and capturing uni-directional communication links help to mitigate and prevent data collision (Chau, Chen and Liew, 2009).

TDMA is based on the allocation of time slots for each networked node to perform data transmission. If time synchronisation can be achieved among the networked nodes, the possibility of data collision is eliminated.

USER REQUIREMENTS ANALYSIS

Besides understanding the intended operating environment, it is critical to analyse user requirements for tactical communication networks. A structured approach is imperative for various subject matter experts (SME) in communications and C2 to jointly analyse the requirements as well as define the network and application parameters. These SMEs possess a good understanding of the operating environment characteristics, radio limitations and application data exchange requirements.

The understanding of expected payload characteristics, types of applications and user-node mobility will shape network design and implementation at the application level. The proposed process shown in Figure 2 aids in analysing user requirements, determining the network design parameters and verifying the network design through simulation. Upon achieving satisfactory simulation results, validation is conducted through field trials and exercises in an actual operating environment and over a representative set-up of the network structure.

Key performance indicators are defined for the assessment and verification of the simulation results. The average message completion rate will determine the reliability of the network in delivering the required payload within the defined operational scenario. The message completion time can

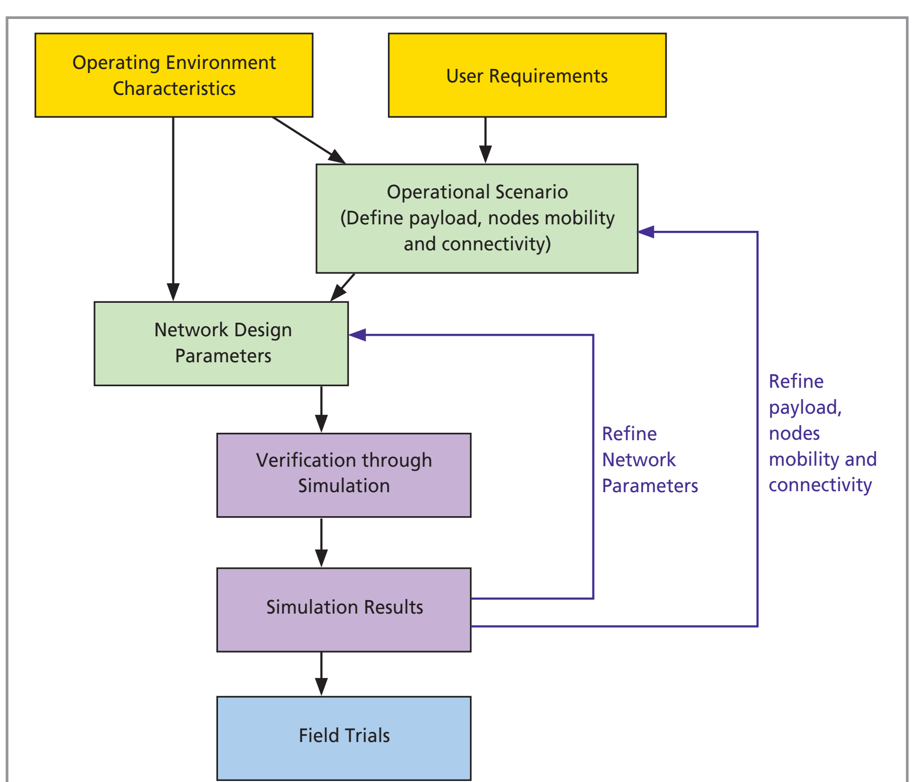

Figure 2. Proposed network design verification process

Payload Type	Data Size	Intended Recipients	Reliability	Frequency
Position Location	≈ 30 bytes	All peers (Broadcast)	No	Periodic
Short Messaging	≈ 150 bytes	Designated (Unicast, Multicast)	Depends on context	Ad hoc
Status Reports	≈ 100 bytes	Designated (Unicast, Multicast)	Yes	Periodic
Orders	≈ 250 bytes	Designated (Unicast, Multicast)	Yes	Periodic

Table 1. Application data payload classification (Source: Adapted from Nakamura, 2008)

also be derived to determine the average time taken to deliver a message across the network, thereby providing estimates of the expected network latency. Unsatisfactory message completion timings could be due to a number of reasons including poor network connectivity that requires data to be re-sent, or transmitting a sizeable payload over a network with limited bandwidth. If the simulation results are unsatisfactory, the network parameters or scenario parameters can be refined for simulation re-runs.

Tactical Command and Control Applications

C2 applications mainly facilitate situational awareness and the effective execution of battle operations. Typical C2 application requirements are used to monitor the locations of friendly forces and adversaries, as well as carry out navigation and battle management functions such as short messaging, status reporting and the issue/execution of orders.

Application Data Payload

It is necessary to manage and regulate the data flow to allow critical information exchange in an environment with limited bandwidth. Receipt acknowledgements for data delivery must be used with care to avoid overloading the network. The application data payload can be categorised in terms of data size, number of intended recipients, requirement for receipt acknowledgement and data sending frequency. Examples of broad categories of payload are illustrated in Table 1.

High Mobility of Tactical Forces

The high mobility of tactical forces results in rapid changes to the network topology. Network topology typically changes when networked nodes appear online and offline intermittently. Depending on physical location, the nodes may appear offline if they go beyond the effective communication range.

The intermittent connectivity may occur when one node disconnects from its current network and connects to another neighbouring network. Self-forming networks in such situations are required to maintain network connectivity. At the inter-network level, sent data are routed to the destination node even if the networked node switches to connect to a neighbouring network.

The defined network design and configuration, along with the data sending requirements and data dissemination implementation, can be verified using network modelling and simulation tools. Communication media models, operating templates and data sending profiles can be set up to verify network design principles and theories, as well as to assess the data traffic loading effects and effective bandwidth utilisation. Simulation is necessary for large-scale network design and validation as the actual network set-up in the operating environment is impractical and resource-intensive.

NETWORK DESIGN FACTORS

To achieve an effective network design, it is essential to study the inherent network characteristics to identify and understand the boundaries of tactical communication networks. These design factors affect the intra-network (single network) functionality, efficiency and performance of the network. Analysis of user requirements is required to obtain the intended deployment, data exchange pattern and intended application usage. This analysis enables better evaluation of design choices and trade-offs for both tactical network deployment and the application implementation.

Medium Access Control Schemes

The legacy VHF/UHF remains the most widely used tactical communication media in the battlefield. The choice of MAC schemes over the tactical communication media is largely dependent on the operating environment and radios used. CSMA is prone to the hidden node phenomenon leading to the occurrence of network instability at high network load (Braten, Voldhaug and Ovsthus, 2008). However, CSMA has a lower control overhead as compared to other MAC protocols and is well suited for quick bursts of very small data sizes.

TDMA is able to overcome the hidden node phenomenon that is observed in some operating environments. By allowing each networked node to take turns and transmit within its allocated time slot, each node is given an equal opportunity to send its data. TDMA is also suited for periodic data sending such as Blue Force Tracking i.e. periodic updates of peer node locations. However, TDMA requires control overheads such as time synchronisation and keep-alive control messages to maintain the network.

Time Slot Allocation

In TDMA, the channel is broken down into time slots of equal duration and these are allocated to nodes for data transmission. Such slots can be pre-assigned prior to a mission, or dynamically allocated as and when required. To perform the latter, it is essential to develop flexibility and operator competence. The number of slots in the TDMA system will be influenced by the number of users in the radio net. Hence, a balance between efficiency and latency has to be maintained. Longer slots increase the proportion of data relative to overheads, while shorter slots can reduce latency between transmissions.

Therefore, it is critical to determine the optimal length of the time slots to be allocated to each node. TDMA slot sizes are determined by packet size and the amount of propagation delay expected in the system. A guard time is built into each slot to ensure that transmissions do not overlap and is guided typically by the longest possible propagation delay.

The Push-To-Talk (PTT) time of a radio indicates the start and end of data transmission. It is also known as the preamble time for the transmitter and receiver. The other time variable affecting effective data transmission involves setting a reasonable time to allow certain data sizes to be sent within a time cycle. Figure 3 shows a simplified breakdown of a time slot structure. PTT delays that are dependent on the radio hardware can affect the performance of the network significantly (Navalekar et al., 2008).

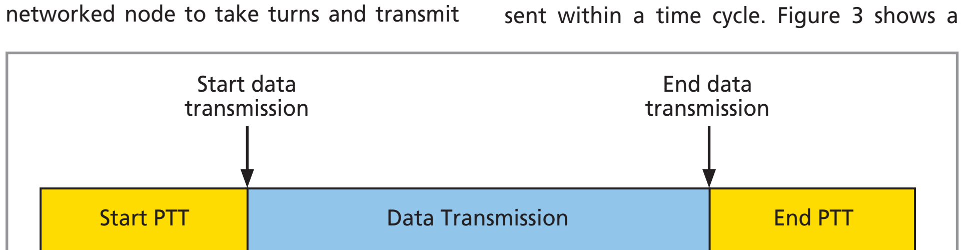

Figure 3. Simplified breakdown of a time slot structure

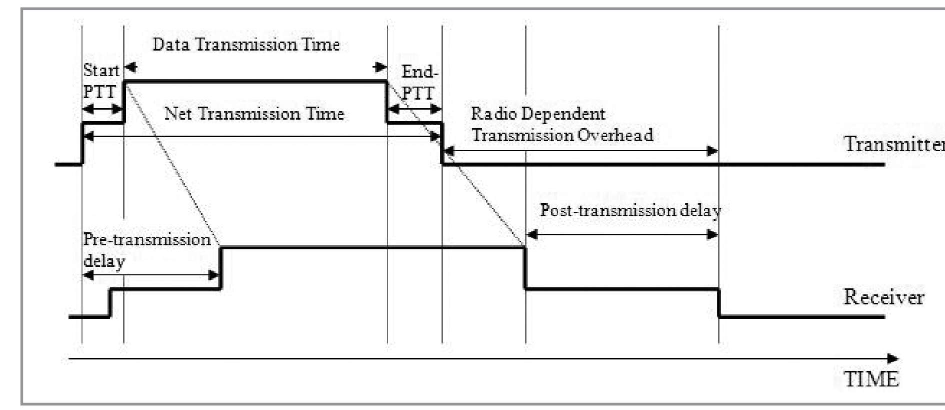

Figure 4. Process of data transmission and receipt

Figure 4 illustrates the process of data transmission and receipt with a breakdown of the relevant time-out expected. At the transmitter's end, the Start-PTT latency is required to ramp up the power amplifier before any data transmission can occur. This is followed by the End-PTT time that indicates the end of transmission. Finally, the transmission overhead time is required to complete the sending of residual data. At the receiver's end, pre-transmission and post-transmission delays are taken into account in order to receive the data completely.

Theoretically, the performance of tactical network access is significantly influenced by the performance of the radio. Receive-to-Transmit *(Rx-Tx)* Turnaround time has a considerable impact on throughput, even for slotted configurations. *Rx-Tx* Turnaround time refers to the time taken for a radio to transit from receiver mode *(Rx)* to transmitter mode *(Tx)*.

To transmit data effectively, the design of the time slot allocation must take into account the typical size of the data sent. For larger data sizes, time slots should be designed adequately to avoid the need to perform data segmentation, as this would require multiple cycles to complete the data transmission. For small data sizes, it is undesirable to allocate large time slots as the bandwidth would be wasted.

Maximum Transmission Unit

Maximum Transmission Unit (MTU) refers to the data payload that can be sent within an allocated time slot. This typically includes application data and header overheads of the preceding network layer information (see Figure 5).

Number of Nodes per Network

Network size is determined primarily by the task group of nodes that communicate with one another frequently. However, in a network environment of limited bandwidth, the network design will also need to take into account the expected update time cycle, bandwidth sharing among the nodes,

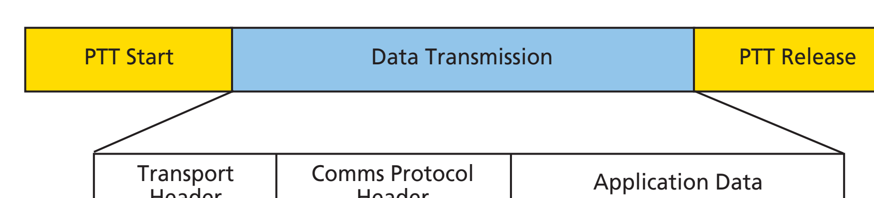

Figure 5. Simplified illustration of MTU

and data sending requirements. These dependency factors will affect the effectiveness of the network design and thereby influence the number of nodes per network.

A short update time cycle for better turnaround time cannot be achieved if the number of nodes per network increases. The available bandwidth and time slot allocation per node are fixed properties of a communication network. With an increased number of nodes per network, the update cycle time would also increase. If the design goal is to maintain the update cycle time, there is a need to re-group the nodes into multiple networks.

Alternatively, the data sending capacity for each node can be decreased to reduce the time slot allocation per node. However, this method may not always be feasible as it is subjected to the user's data sending requirements and the fixed portion of the time slot.

Data Update Cycle Time

There is a common misconception that radios with a higher data rate will improve the data cycle time. If the time slot allocation and number of nodes remain constant, the update cycle time will also remain constant. However, a higher data rate allows more data to be sent within the time slot and this is useful for large data transmissions. Other network design considerations that can increase network efficiency include minimising transmission overheads, designing small application data sizes, and defining the optimal periodic sending of control messages.

Large transmission overheads have a significant impact on update rate regardless of the radio data rate. This is more evident for small data sizes in view of the higher overhead percentage compared to large data sizes. The application data sizes are designed to be small for the data link protocol to consolidate multiple small data packets in a single transmission, thereby improving data update rate and network efficiency. Periodic sending of network control messages should also be optimised for network efficiency by combining multiple control messages in a single transmission, or by synchronising with the rate at which application data is sent.

Network Throughput

In our work with the Singapore Armed Forces (SAF), we observed that network throughput not only is influenced by the data rate of the communication media, it is also dependent on other factors such as time slot allocation and transmission overheads. Doubling the data rate of communication media does not double the network throughput (Wang et al., 2007). The non-linear relationship between network throughput and bandwidth is more significant for small data sizes than for large ones. The variable network throughput is also due to unreliable or intermittent network connectivity of mobile nodes which require multi-hop routing.

Factors Influencing Network Design

Network design is a trade-off between radio and network effects. Available network design choices must be analysed to achieve the desired operational network effects. Figure 6 provides a summary of the casual factors of network design and their relationships.

GUIDING PRINCIPLES FOR NETWORK DESIGN AND CONFIGURATION

The proposed step-by-step engineering guiding principles involve requirement analysis with a clear understanding of users' needs, the operating environment and network design factors. The operation of tactical communication networks requires the consideration of suitable adaptation mechanisms for designing both intra-networks and inter-networks (across multiple networks). A holistic approach in network design is required at the various layers,

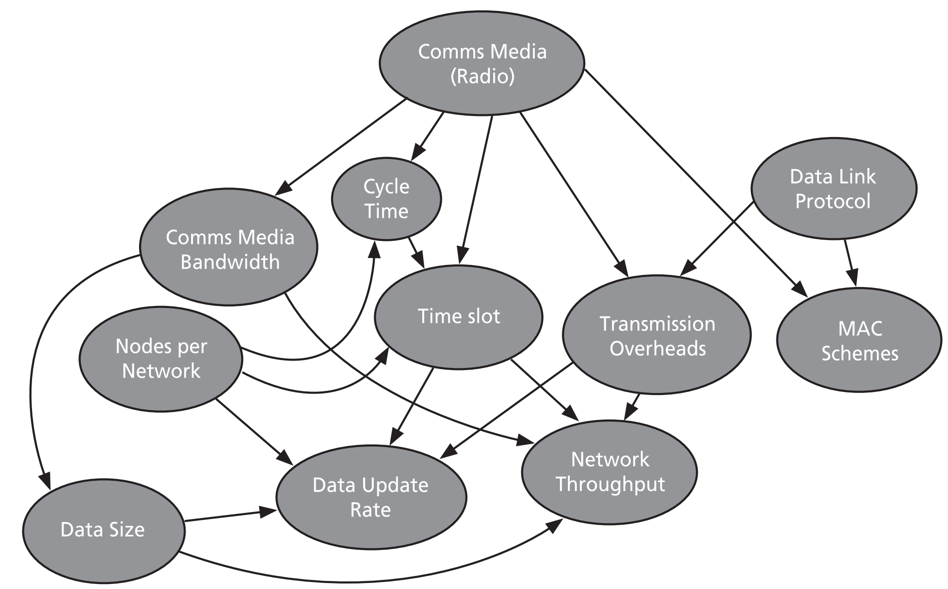

Figure 6. Causal factors influencing network design

which may take the form of ensuring that network properties are suitably defined and configured. In addition, adaptation mechanisms are required to manage the network load and utilisation during application.

Communication Network Characteristics

The first principle of network configuration is to understand the network characteristics and identify their boundaries. Network characteristics include communication link reliability, bandwidth availability, network mobility, network access type and supportability. If the network characteristics are clearly understood, the appropriate network properties such as the network hierarchy level, expected latency and the gateway across transit networks can be configured effectively.

Data Bandwidth Availability

The key element of engineering the network design configuration is to determine the effective data bandwidth. The cost effectiveness of network routing is dependent on the efficient utilisation of available data bandwidth. Taking into account bandwidth availability and user requirements analysis, suitable adaptation mechanisms may have to be incorporated in the data link routing protocol (middleware) or in the application layer to ensure network performance and efficiency.

There are several adaptation mechanisms that should be considered when working with a limited-bandwidth network:

- **Reduce transmission overheads**. Data packets will ride on application data payload, while multiple small data packets are consolidated in a single data transmission.

- **Limit application data payloads.** Methods such as data compression and pre-formatting application messages can reduce application data payloads to levels that are supportable by available bandwidth.

- **Adopt effective means of disseminating data.** Methods include broadcast messaging to send periodic location information, multicast messaging for multiple recipients, as well as publish and subscribe for quick dissemination of information across transitional networks.

- **Prioritise data messages** to minimise latency for urgent critical data.

• **Design application payload with data resolution differentiation** for discarding detailed data when routing from high to low bandwidth networks. This mechanism allows only critical data to be sent, and prevents a bottleneck from building up when routing through low-bandwidth networks, especially for potentially large data sizes such as images and file attachments.

Data Sending Requirements

To ensure success and effectiveness in network design, data sending patterns and requirements within and across networks have to be analysed. Data sending patterns can be inspected through the following ways:

• Identify application and control data that must be sent periodically

• Identify application data type and size that must be sent within and across networks

• Assess expected data routing flow, including the identification of nodes that require communication with one another, their frequency, and the number of inter-networking routing from sender to recipient nodes

After the data sending patterns are assessed and determined, the effective MTU can be computed based on the data sending frequency and typical data payload required.

Time Slot Allocation Configuration

To achieve effective data transmission, time slot allocation must be optimised for the required data size and the fixed PTT time. Time slot optimisation may be based on size of the data sent frequently, or the consolidated size of the data sent periodically.

For example, a time slot allocation of two seconds may include more than one second of fixed PTT time with tolerance. This leaves less than one second to send useful data across the network. With a network of 10 nodes, each time cycle will be 20 seconds. This means that a networked node will be able to send data every 20 seconds and the update cycle time is 20 seconds.

In addition, the optimal time slot configuration must include a buffer for network control messages, or have a provision for gateway nodes to perform intra-network or inter-network routing.

Number of Nodes per Network Configuration

While sending data between nodes configured within the same network is expected to be faster with inter-network routing removed, an excessive number of configured nodes in a network will affect its overall latency and responsiveness. There is a need to strike a balance among the dependency factors of expected update cycle time, bandwidth sharing among networked nodes, and data sending requirements. These dependency factors affect the effectiveness of network design.

In order to achieve an optimal update cycle time for a better turnaround time, nodes will need to be re-grouped into multiple networks. Data sending capacity for each node will need to be assessed for the opportunity to reduce the time slot allocation per node. However, this method may not always be feasible as it is subjected to the user's data sending requirements and the fixed portion of the time slot.

Infrastructure Support for Battlefield Communication

The basic principle for establishing the communication infrastructure is to leverage current network resources and capabilities to achieve the communication network effect. A tactical communication network typically comprises heterogeneous communication media. The network design configuration should take into account the capabilities of each communication medium to design the overarching network architecture and deploy the appropriate communication media at the different network architecture levels.

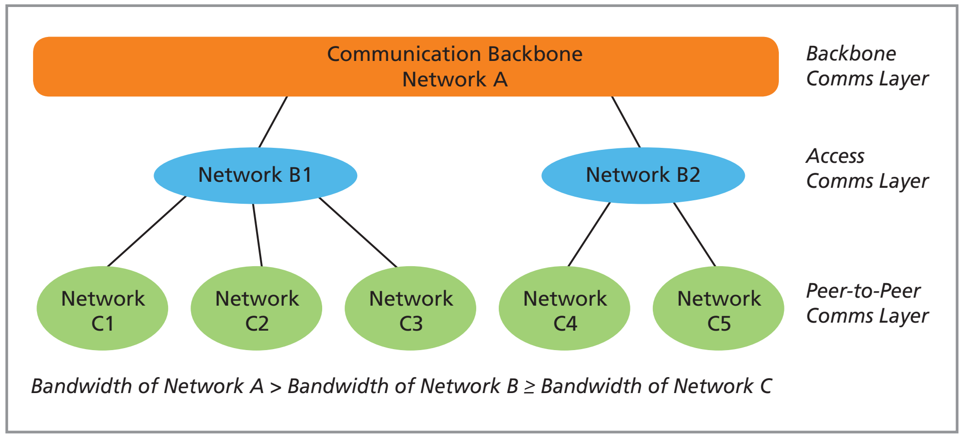

Figure 7. Hierarchical architecture of a communication network

The hierarchical communication network architecture illustrated in Figure 7 shows how a battlefield communication infrastructure is essential to provide routing support across all network layers. Higher level networks are equipped with higher bandwidth communication media, which facilitates routing across peer networks that are linked to access networks. The battlefield communication infrastructure will also facilitate network management at the higher hierarchical level to facilitate smooth information flow as well as network monitoring and control.

Adaptation at Application Level

There are several application adaptation mechanisms and data dissemination techniques that should be considered for implementation at the application level to manage network load and utilisation:

Data Compression

Data compression techniques should be applied to further reduce the data size to be sent over the tactical networks.

Resolution of Critical Data

The size of data sent over communication channels with limited bandwidth should be regulated. Techniques to send data with differentiated resolution need to be implemented to ensure that only critical information is sent to the recipients with access to limited bandwidth. Detailed information can be omitted to ensure that only critical information arrives at the destination in a timely manner.

Data Structure Format

Operational data that is required for transmission over tactical networks should be structured as a formatted message to minimise overheads. Data should be represented in a numerical form instead of the actual value or full description i.e. bit-oriented messages. It is not recommended to send large application data and files through tactical networks.

Data Sending Frequency

The frequency of sending application data and system management messages needs to be synchronised and controlled to regulate the overall data traffic over the limited-bandwidth network.

Acknowledgement and Priority

The operational data and supportability of data loading in the network should be balanced. While it may be good to send application data at high priority together with the delivery and receipt acknowledgement, priority has to be assigned to the data due to the limited bandwidth available. It is essential to exercise prudence in defining mission-critical data that require urgent and immediate sending, and receipt acknowledgement.

If the appropriate data dissemination mechanisms are used, bandwidth will be utilised more effectively in data traffic loading. The following data dissemination mechanisms are recommended in view of data sending requirements.

Broadcast Messaging

Broadcast messaging is an effective way of sharing data with peers within the same network. By broadcasting one's location and sending situation reports, all the networked nodes within the same network will receive the data. Data efficiency is achieved without having to send multiple copies of the same data to everyone in the same network.

Multicast Messaging

Data dissemination methods using multicast send a single copy to a recognised group address. Hence, networked nodes that belong to the group address will receive the data sent.

Publish and Subscribe

The Publish and Subscribe mechanism allows users to subscribe to a specific topic or area of interest. This offers an effective method for the quick dissemination of information to the relevant parties.

Managing Classified Information Flow

To manage classified information flow across networks, it is critical to assign the appropriate security classifications to the application data and the network.

CONCLUSION

To ensure effectiveness of the network in providing a reliable communication link in the tactical land environment, several factors for network design configuration have to be considered. The proposed principles and design considerations provide guidance in evaluating available design choices and analysing effective trade-offs for tactical network deployment and application implementation. To achieve effective data communication and exchange over a networked system, C2 applications must take into account the communication networking environment, and have the ability to adapt and factor in physical communication media constraints and network limitations. The ideal solution is to combine the designs of communication networks and C2 applications.

In the future, technology advances may lead to the availability of higher capability or hybrid communication media which will have to be supported. The guiding principles and key design considerations should remain relevant but adaptation and configuration techniques may need to be reassessed for relevance.

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BIOGRAPHY

Lai Ying Cheung is Head Engineering (Communications). Besides leading technical development in the Communications area, he also steers the build-up of future communications capabilities and harmonises organisational engineering processes, methods and tools. He was involved in numerous communications related projects that have contributed to the build-up of the Singapore Armed Forces (SAF) communications and networking capabilities. He was part of the Integrated Communication System Programme team which won the Defence Technology Prize Team Award in 1992. He obtained a Master of Science (Electrical Engineering) degree from the National University of Singapore (NUS) in 1990 and a Master of Business Administration (Management of Information Technology) degree from Nanyang Technological University in 1997.

Chia Wan Yin is a Principal Engineer (Networked Systems). She is involved in systems integrations and data link related works, ensuring end-to-end networked systems interoperability. She also manages the acquisition and implementation of Command and Control systems and data link communication protocol. Wan Yin is one of the recipients of the Defence Technology Prize Team (Engineering) Award in 2006 for the design and development of compact marine craft for the SAF. She obtained a Master of Science (Defence Technology and Systems) degree from NUS in 2010 and a Master of Science (Computer Science) degree from the Naval Postgraduate School, US in 2010.