Mesh network: Increasing resilience and reducing infrastructure across network domains

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Tactical communication networks have until recently been based mostly on point-to-multipoint near-line-of-sight networks, principally in the very-high frequency band. This arrangement is now being replaced by MANET technology, which offers a more resilient and flexible communications architecture. *Giles Ebbutt* reports

Mobile ad-hoc network (MANET) technology provides a self-forming, self-healing communications mesh network in which the radios automatically connect to build out the network, with each acting as an autonomous, repeater node within it. The most frequently noted advantages of this technology are that there is no infrastructure, it is resilient, and network management is minimal.

MANET waveforms carry voice and data to a large group of mobile users. This capability enables real-time integration into applications that use GPS, video, and digital data alongside voice communications such as the Tactical Assault Kit (TAK) that provides dismounted situational awareness (DSA).

Often coupled with the MANET concept is multiple-input, multiple-output (MIMO) technology, through which the capacity of a radio link is increased by using the transmission and reception from more than one antenna to take advantage of signal multipaths.

The Domo Tactical Communications NETNode2x5W-5RM MANET radio mounted on a Hippo unmanned ground vehicle during British Army trials. (Domo Tactical Communications)

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Rob Garth, product director at Domo Tactical Communications (DTC), explained to *Janes* that in a MANET data is automatically routed from the source to the destination by different methods. Some systems take a 'flooding' approach with multiple retransmissions to ensure successful data passage. Others use a 'contention-based' channel access mechanism called Carrier Sensed Multiple Access in which radios with data to send wait until they can see a clear channel before transmitting. This can lead to self-interference when several radios try to transmit simultaneously, resulting in multiple retries and a reduction in network capacity.

Garth said DTC uses a "cost table" mechanism to determine the most efficient route via different nodes on the network. The cost table algorithm allocates a 'cost' to each link between nodes based on its quality. Route selection takes into account the quality of the links within the network and the required number of hops between nodes, with the system automatically routing data according to the lowest cost route.

Garth said DTC also uses a token-based managed channel access mechanism in which only a radio holding the channel access token can transmit, which he claimed offers much lower latency and more efficient channel utilisation, resulting in higher throughput for user applications.

"A well-designed MANET is extremely robust and easily copes with mounted and dismounted scenarios where links appear and disappear irregularly in the course of operations," Garth said. "It is hugely flexible and scales very easily from two to more than 100 nodes with very few disadvantages."

According to Garth, MANET technology emerged because of several developments. "IP [Internet Protocol] networks are pretty ubiquitous now and a MANET mesh drops into an IP networking infrastructure very easily," he noted. This has been coupled with the development of suitable hardware, system-on-a-chip processing devices, and low-cost platforms, with widespread militarisation of the concept taking place in the last six years or so. The higher expectations of the modern user have also played a part: MANET provides the smartphone-like connectivity they have come to expect.

Garth said the critical concept distinguishing MANET from early infrastructure mesh models is that there is no central routing authority so there is no single point of failure. Each node can independently work out how to route data, making the system entirely autonomous. As each node acts as a repeater, ranges can easily be extended, such as by using an unmanned aerial vehicle (UAV). As this is an automatic process, no routing planning is required, which Garth said "seriously reduces the overheads in planning and management".

Where network 'islands' are not in range of each other, even by 'daisy chaining' nodes, they can be linked using other high-capacity communications means such as satellite communications (satcom) or point-to-point microwaves using a gateway device. Garth observed that typical military networks are organised on a hierarchical basis that reflect organisations and that networks are now not only being deployed at the lowest organisational level but also at the next highest, with separate networks linked by a gateway node that is connected to both networks via a range of communications modes and may also manage a transition between security domains.

Defensive measures

Garth explained that there are ways of adding biassing to the route selection in order to improve the low probability of intercept (LPI) and low probability of detection (LPD) qualities, adding that this was becoming increasingly important due to an increased electronic warfare (EW) threat. Users are becoming more alert to methods of network deployment and use to improve LPI/LPD, he noted.

As well as the system autonomously selecting the best route, he said that DTC has developed an interference avoidance system that selects the best frequency available. Every node in the network listens to a number of frequencies and reports the noise level; the network autonomously responds accordingly and utilises the quietest frequencies, which offers a defence against jamming.

Domo Tactical Communications' latest NETNode2x15W-5RH MANET radio, used by customers on medium-altitude, long-endurance UAVs. (Domo Tactical Communications)

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Garth emphasised that the key element of MANET is the waveform, noting that the one used "has a material effect on the network particularly in multipath or contested/congested environments with interference or jamming so having the right waveform is key and for optimum performance it needs to be specially designed".

Waveform and channel access mechanisms are the principle distinguishing features between different MANET manufacturers. DTC's latest waveform is called MeshUltra, which Garth said has increased throughput and scalability, as well as resilience in contested environments. It employs more than 800 carriers, which enables a lower symbol rate on each carrier and therefore,

he claimed, a much better resistance to long-range multipath reflections. He noted that it has also performed particularly well in wet woodland, achieving “very good penetration”.

DTC utilises frequencies from UHF (320–470 MHz) up to C-band SHF (5.5–6 GHz) and its range of equipment includes a triband radio covering L-, S-, and C-band. Garth said DTC radios can typically access 7–800 MHz of spectrum within each band and offer throughput of up to 87 Mb/s in 20 MHz channels and up to 5.6 Mb/s in a narrow 1.25 MHz channel.

Garth noted that spectrum availability is a constraint, particularly in seeking longer ranges between nodes. Long-range links need to operate in a more robust mode in order to achieve the greater range, which means using narrow channels. However, narrow channels have a lower data throughput so sending the same amount of data over a long-range link can take more of the available channel capacity than sending the same amount over a short-range link. As a result, it can be more efficient to use two short hops using less channel capacity rather than one long hop.

L3Harris Technologies' AN/PRC-163 is one of the two radios selected as the handheld variant of the US Army HMS radio programme, which will run the TrellisWare TSM waveform. (L3Harris)
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He explained that currently most mesh networks do not generally use frequency hopping technology and most use multicarrier coded orthogonal frequency division multiplexing waveforms, which use multiple carriers with the data interleaved among the carriers. Garth said this is particularly good for use in multipath environments, such as urban areas where signals can be reflected from a number of surfaces, in that it provides better multipath rejection.

Waveforms and the hardware that hosts them are separate elements, and the former can be supplied on a standalone basis. DTC has provided its waveform to the Indian Army in a project in conjunction with Nokia to provide a high-capacity backhaul network using LTE radios but its solutions predominantly include hardware platforms that have a software-defined radio (SDR) architecture.

Nigel Lee, DTC vice-president for sales, said that DTC's range of platforms included the Solo8 radio that he claimed is "the world's smallest and lightest MIMO mesh radio". He said that it was smaller than a matchbox and that customers deploying it in air-ground mode were achieving node-node ranges of up to 300 km.

These were mostly in UAVs, he said, but also in some surveillance aircraft. DTC's MANET technology was also being used to support swarming UAVs where there was a mix of large and small platforms and a requirement for long- and short-range communication. He suggested that a network of diverse platforms favoured a mesh solution as this can offer radios with different capabilities in a single network, including reachback.

Lee said that in India DTC MANET radios have flown on a swarm of 26 UAVs as part of a disaster relief trials programme, adding that the company is also working on nanoUAS and UAV swarming with other unspecified international air forces. A DTC MANET mesh was also used by QinetiQ when it demonstrated manned/unmanned teaming (MUM-T) in June 2020 using an Airbus H125 helicopter and a small UAV.

Lee noted that MANET radios could be especially useful in a maritime environment for boarding operations. Because all nodes in the mesh are repeaters, all members of a boarding team could communicate with each other between decks. The network could be extended back to the command ship using an additional range-extending node on another platform such as a tactical UAV or a boat, providing voice and video to the command team in real time.

An example of this range extension capability was demonstrated by using a node mounted on a Helikite Aerostat during the NATO Recognized Environment Picture Maritime Unmanned Systems (REPMUS) exercise in late 2019.

DTC is also working on MANET communications for unmanned surface vessels (USVs), specifically equipping BAE Systems's Pacific 950 and Pacific 24 boats and L3ASV's C-Target 9 USV, as well as being in use in the Thales-led UK/French autonomous maritime mine-countermeasures project. The Pac950 and CT-9 have been used in the UK's Autonomous

Advanced Force experiments. A USV experimentation range off the south coast of England has also been equipped with a MANET mesh using DTC radios.

US Army programmes

The US Army has been a significant adopter of MANET technology via the development of its Integrated Tactical Network (ITN), which is part of its Network Modernisation programme. It is also fundamental to the Integrated Visual Augmentation System (IVAS) programme and other efforts.

Colonel Garth Winterle, project manager, tactical radios, programme executive office command, control, communications – tactical (PEO C3T), told *Janes* that MANET technology is "extremely effective for dismounted and other types of manoeuvre operations as it provides combined voice and data communications and overcomes obstacles and other line-of-site challenges".

He said an advantage is the connectivity assurance mesh offers. "Provided you're connected to that one soldier or vehicle next to you, you're connected to the network and you know if you're connected or not so you know whether your message is getting through," he noted.

Col Winterle observed that MANET has not replaced more traditional line-of-sight (LOS) and beyond-LOS (BLOS) waveforms but it improves the number of PACE (primary, alternate, contingency, and emergency) communications options available. The selection of the most applicable technology depends on who you are communicating with and what for.

The TSM waveform from Trellisware Technologies, which is software defined and hardware agnostic, was selected by the US Army as the threshold MANET waveform requirement for its handheld, manpack, and small form fit (HMS) radio's Program of Record. Col Winterle said that the adoption of TSM was a major effort in the ITN.

The HMS Program of Record covers the single-channel radio (SCR) for a dismounted soldier that is yet to be selected; the two-channel handheld, provided by Thales (AN/PRC-148D) and L3Harris (AN/PRC-163); and the two-channel manpack, awarded to L3Harris (AN/PRC-158) and Collins Aerospace (AN/PRC-162). The SCR will run only the TSM waveform while the manpack and handheld will run it in addition to other waveforms. All three radio types can therefore operate a TSM-based mesh network that can pass voice, data, and position location information (PLI).

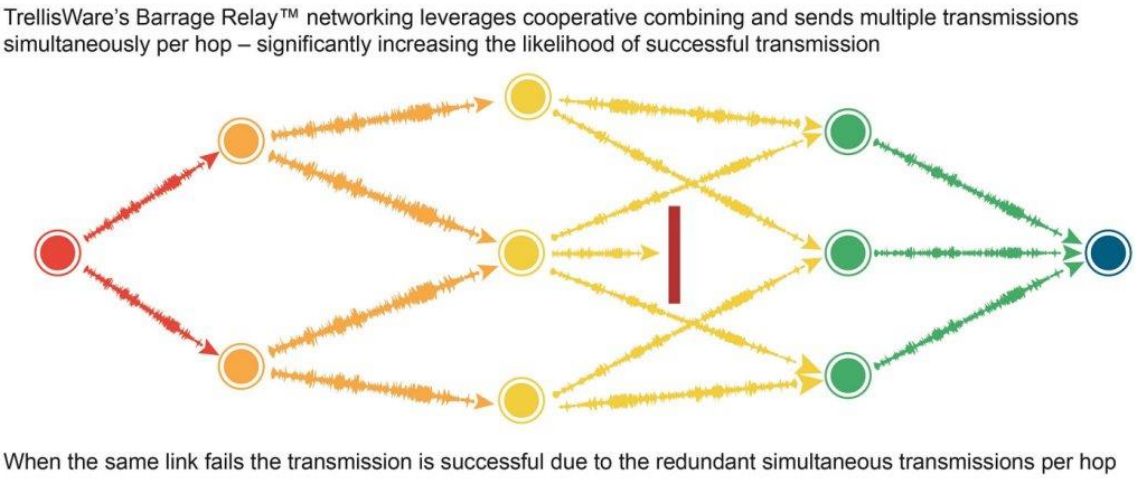
The SCR, running a single waveform, will operate in the secure-but-unclassified (SBU) domain that the army is adopting for use at battalion level and below. Col Winterle said this limited specification would enable increased numbers of radios to be acquired as they will be more affordable.

All are being fielded as part of Capability Set 21 (CS21): the first tranche of the army's biennial network modernisation effort, which is being fielded to four infantry brigade combat teams this year. Possible contenders for the SCR will be included.

TrellisWare's TSM

Haidong Wang, vice-president, product management and strategic partnerships for TrellisWare, told *Janes* that the concept of an autonomously managed, self-healing, and self-adapting network with no infrastructure originated in academia around the turn of the century. The US Army's Joint Tactical Radio System programme, which aimed to provide an all-embracing network as part of the ill-fated Future Combat System and from which the HMS Program of Record evolved, provided a boost to the development of the concept for military use, he said.

Wang observed that the problem with the MANET solution at that stage was that merely maintaining network connectivity required a capacity overhead irrespective of the level of traffic. If the network increased in size, not only did the overhead grow exponentially but increased frequency spectrum was required.



A graphic illustrating the TrellisWare Barrage relay MANET technology. (TrellisWare)

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Matt Fallows, TrellisWare vice-president of global business development and customer support, said that to overcome this TrellisWare, which has academic roots, had developed the TSM waveform. This provides what the company calls Barrage Relay networking, which instead of topology control uses proprietary technology meant to significantly reduce the overhead requirement. He said this enabled up to 800 radios to operate in a single radio frequency (RF) channel network.

He observed that in contested environments smaller networks offer fewer alternative routes and larger, denser networks work better as they provide more alternative routes to avoid interference.

Fallows said that "a lot of work" had gone into proving the TSM waveform effectiveness with Type 1 encryption and SBU security level. He added that TSM is "very effective in supporting multiple [security] enclaves in one network".

He also emphasised the importance of frequency spectrum efficiency, which he said is a continuing challenge as there is "an insatiable demand for spectrum, with pressure on the military from commercial interests to relinquish it, already demonstrated through the loss of government

frequencies to 4G and 5G". Spectrum availability is shrinking, he said, which makes its efficient use all the more important.

Wang suggested that there are two architecture options for employing MANET technology – hierarchical networks with gateways between them or a single flat network – and that there is a continuing philosophical debate between the two. He said network architecture had previously been designed based on the force structure as opposed to optimising the network to take advantage of scalability and offering flexible options for commanders when deploying their forces.

This was reflected in early assumptions that the network hierarchy should mirror the military hierarchy, he said, but the US Army had now opted for the flat network option. "You can still support different command hierarchies on a flat network," Wang said, "by using different talk groups and logical subnets". Col Winterle said that TSM allows up to 32 different talk groups on the same network and, although these may reflect a hierarchical organisation, the mesh "provides leaders with greater opportunities to move around the talk groups".

Colonel Rob Ryan, deputy director, network cross-functional team for the US Army, added that, although the hierarchy still exists, the ability to move data around is "dramatically different, improving the speed of decision and action", which is enabled by MANET technology. He noted that the use of hardware agnostic waveforms also enables new technology, either in terms of improved hardware or upgraded waveforms, to be imported over time.

TSM was also chosen as the waveform for the Special Operations Forces Tactical Communications programme for handheld and manpack radios that are now being fielded, running the TSM waveform. Contracts for both of these were awarded to L3Harris: USD390 million for the handheld (AN/PRC-163) in 2015 and USD255 million for the manpack (AN/PRC-167) in 2017. Fallows said that TrellisWare was also working with other 'Five Eyes' countries special forces, as well as other international experimentation and modernisation programmes, although he was unable to elaborate further.

He explained that TrellisWare is focused on acting as a third-party technology provider for the larger US military programmes and for international customers, agnostic to the hardware platforms. However, he said TrellisWare also supplies its own hardware but it tends to be for a small customer set such as special purpose programmes, the special forces community, and government agencies that tend to require small form-factor, customer-focused hardware solutions. He noted that these limited programmes often drive innovation and influence wider development.

Fallows noted that TrellisWare was selected by the C5ISR Centre at the US Army's Combat Capabilities Development Command as the prime developer of the Warrior Robust Enhanced Network-Narrowband (WREN-NB) waveform, which is a fast frequency-hopping waveform and is MANET-capable for voice, data, and PLI. It is hardware agnostic and has been ported onto the HMS manpack and handheld radios; development is now complete.

Wang said that WREN-NB was developed to mitigate EW threats and it will be incorporated in future US Army capability sets. He believed that further waveform development would address increased defensive measures and that "as a technology company we are working on this to improve communication resilience in contested environments". He also observed that future

communications networks were likely to involve complex but seamless multidomain communication architectures, with transparent switching between different communications modes by leveraging advanced machine learning (ML) capabilities.

Silvus Technologies

Silvus Technologies is also involved in military MANET technology development, including for the US Army and other programmes. Jimi Henderson, vice-president of sales for the company, said legacy waveforms "were originally designed primarily to support voice transmission and lacked the throughput required for today's missions, such as the need to support the transmission of video and radar data".

In the decade before 2010, the US Defense Advanced Research Projects Agency (DARPA) identified the need for greater bandwidth in tactical networks as a key capability gap and, Henderson said, funded Silvus under a USD15 million contract to develop a MIMO-enabled MANET system that could "operate at the tactical edge", providing increased range, throughput, and signal reliability. He said that although MIMO technology already existed in commercial markets – for example in Wi-Fi, WiMax, and LTE, with beneficial effects – the problems of mobility, range, and interference that are typical of conditions at the tactical edge had not been addressed and this was what DARPA had funded Silvus to look at.

Silvus Technologies' new SL4200 radio runs the MN-MIMO waveform in narrowband channels down to 1.25 MHz. (Silvus Technologies)

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Henderson said, as a result, Silvus fielded what he claimed was "the first tactical MIMO radio" in 2011. The company has continued the MIMO and MANET developmental path, principally with its range of StreamCaster radios and its latest Mobile Networked MIMO (MN-MIMO) waveform. He said that the waveform could be ported onto third-party hardware platforms.

Silvus radios offer more than 30 combinations of frequency bands, Henderson said, ranging from 400 MHz to 6 GHz. Its dual-band radios enable the use of two disparate bands in a single radio without the need to swap hardware, with a single frequency in use at any moment. "You can move an entire network from one centre frequency to another with a single button click from any node," he said, adding that the network management graphic-user interface had been specially designed for use with small screens and therefore by dismounted users with a chest-mounted user interface device.

Henderson noted that EW threats from possible peer or near-peer adversaries are demonstrably real and that there is a strong focus on this from the US military, Silvus's principal customer, which is "seeking spectrum superiority".

Defensive innovations were therefore driving development and Silvus is implementing anti-jam technologies in what it calls a Spectrum Dominance Package. In January 2019 it launched the MANET Interference Avoidance (MAN-IA) mode of MN-MIMO, which can scan up to six channels across two disparate frequency bands, detect interference, and automatically switch the network to an interference-free channel.

In January Silvus revealed the MANET Interference Cancellation (MAN-IC) mode of MN-MIMO, which provides further anti-jam capabilities. This uses a technique called Eigen beam nulling, in which the system looks at the amplitude and phase of the jamming signal from the perspective of each antenna and identifies its spatial characteristics, enabling the jamming signal to be spatially filtered out from the intended signal.

Henderson said this can suppress the jammer by up to 30 dB – the jammer would require 1,000 times more power to achieve the same effect – and if used at that level it is exposed to counter action.

At the same time Silvus also launched MANET power control, which Henderson said reduces the network's RF footprint. He explained that this throttles the power down to the lowest level necessary to maintain links in the network, dynamically adjusting the power as required.

It has also introduced a technique called transmit Eigen beamforming, which is similar to beam nulling but intended to amplify a signal rather than eliminate it. Beamforming manipulates the transmit antenna phase and amplitude to guarantee that when two signals arrive at the receiving antenna they arrive in phase and therefore maximise the signal strength. Henderson said that in a LOS channel this can deliver a boost of up to 6 dB, effectively giving an 8 W radio the equivalent of a 32 W output and increasing the reliability of the network, and giving a non-LOS (NLOS) channel more pronounced benefits.

A Silvus Technologies StreamCaster radio mounted on a Ghost Robotics V60 legged unmanned ground vehicle during a USAF ABMS Onramp Experiment. (Silvus Technologies)

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Silvus has also launched new versions of the StreamCaster SC4200 and SC4400 radios that increase power outputs from 4W and 8W to 10W and 20W, respectively, as well as a low size, weight, and power (SWaP) version, the SL4200, that runs the MN-MIMO waveform in narrowband channels down to 1.25 MHz.

Silvus is supplying the SC4200 and SC4400 radios to the US Army as part of the ITN fielding, providing mid-tier high-capacity LOS backhaul connectivity between brigade and battalion command posts. The initial tranche in CS21 will be the existing version of the radio, Henderson said, but the spectrum dominance package and the new radio versions are expected to be inserted for Capability Set 23 (CS23).

Silvus is also supporting the US Air Force's (USAF's) Advanced Battle Management System (ABMS) project, which seeks to rapidly connect sensors to shooters across multiple domains. Part of this is a MANET known as MeshONE that Henderson said "connects all the tactical edge elements". Silvus has provided this in two experimental events so far known as Onramp 1 and 2. Henderson said it "had had a lot of success" in these and that ABMS was an iterative programme in which Silvus was continuing to participate.

Moreover, Silvus and DTC have been selected for the prototype phase of the IVAS programme. IVAS is an augmented-reality, head-mounted display based on the Microsoft Hololens that is meant to provide dismounted soldiers with situational awareness (SA) and other information directly into the field of view. The IVAS requirement is for a low SWaP single channel radio that provides mesh networking for voice and data, and is capable of transporting TAK data.

Henderson said Silvus had supplied more than 1,000 radios for the IVAS development trials and there had been three soldier touch points (STPs) so far. STP 4 is due in the next few months, he said. DTC has also supplied a similar number of radios specifically developed for the programme using its MeshUltra waveform.

Ultimately the IVAS programme will require 100,000 radios but the IVAS waveform is not yet mandated and the intention is to look at multiple vendors who will offer different MANET solutions. Col Winterle said there would be what he described as a "vendor shootout" to determine the eventual selection that will also be driven by affordability. Whatever the outcome, he said, "We will need to make sure we have a bridge into the larger TSM networks fielded on ITN platforms" and this was part of the IVAS programme's remit.

He also said that currently the Nett Warrior dismounted soldier SA system was paired with the leader radio using TSM but the IVAS radio solution might offset the numbers required for Nett Warrior. "We won't have both," he said, "and there could be a merging of requirements".

The MANET waveform solutions used in these US programmes are only a sample of what is available, with most SDR platform manufacturers offering their own, as well as hosting third-party waveforms. L3Harris, for example, has an extensive global footprint for its hardware, and Shane Eisenman, senior scientist, communication systems, told *Janes* , "MANETs are central to all tactical communication modernisation efforts that L3Harris is engaged with today and in many cases are already well-established with fielded systems. The USMC [US Marine Corps] uses our …

Advanced Networking Wideband Waveform on the AN/PRC-117G as their Type 1 secure MANET [and it] is also used extensively by several international customers in Europe and Asia."

Eisenman also noted that L3Harris has developed a suite of MANET-TDMA Networking Waveforms (TNW) for the "internationally focused" RF-7850 platform. This includes the Soldier-TNW that is designed for voice, data, and PLI information; V-TNW that maximises data throughput; and TNW-75: a narrow-band waveform using a 75 kHz channel. He said these solutions had been adopted in a range of international modernisation programmes.

Future developments

Looking to the future, Col Winterle said that the US Joint Tactical Networking Centre was conducting research into new waveforms and that these have to be assessed for technical implementation and business case. The greatest cost of porting a new waveform onto an in-service SDR is reconciling the differences between the in-service SDR and the SDR it was developed on. "If you want to introduce a new waveform you have to calculate the probable cost of doing so. It might be cheaper to buy a quantity of new radios and incorporate them into the architecture using gateways," he explained.

Integrating a network with joint and coalition partners was also an issue, Col Winterle said. To some extent this is an application issue, "Can I build an application that will work on two networks used by different partners using [the] same waveform so they can operate together?" The UK, for example, is adopting TSM for the initial phases of its DSA programme.

However, he also noted that with some MANET waveforms (such as TSM) a user only has access to the data they are cleared for but each node relays all the data, providing a multilevel capability. CS23 will focus on this, he said, noting that management needed to be kept simple and intuitive for the user.

The Capability Set 3 (CS 3) militarised form-factor prototype of IVAS during an STP 3 squad reconnaissance mission test event at Fort Pickett, Virginia, in October 2020. Domo Tactical Communications and Silvus Technologies provided MANET radios for the IVAS trials. (US Army/Courtney Bacon)

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Col Ryan noted the importance of the army's Project Convergence (PC) experimentation programme in examining possible expansion of MANET usage, such as integrating new satcom capabilities into mesh networks. He also highlighted the impact of artificial intelligence (AI) and ML, the development of cross-domain solutions, and the impact of mesh networks on communications doctrine, and said PC will enable experimentation in all of this.

Garth said that future development of MANET technology was likely to be driven by a greater demand for dynamic spectrum access, with radios that were cognisant of the mission environment and could change the way they operate to take account of it, particularly for the dismounted user. He suggested this could include measures such as changing frequency and altering sensor modes to match data capacity or automatically altering modes and data usage to match the expected length and nature of a mission in order to preserve battery power. He added that such cognitive radios could utilise ML based on previous experience and current network conditions.

Garth also suggested there would be an increased requirement for MANET radios utilising multiple frequency bands, a greater demand for different combinations of frequency bands, and increased scalability of channel bandwidths and number of nodes.

Similarly, Henderson believes future development will focus on network management, which will increasingly be autonomous and utilise ML to enable the system to select the correct management tools at the correct time.

Eisenman noted that simple and intuitive network management tools will be required to enable "quick, error-free configuration" and, like others, identified defensive EW techniques as being a key future requirement. It also emphasised the importance of waveform hardware agnosticism.

Comment

The use of MANET technology is spreading across domains because of the advantages it offers by reducing infrastructure requirements and increasing resilience. Defensive electronic warfare measures are likely to be the focus of future development, together with the development of cognitive radios and increasingly sophisticated and capable waveforms.