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16. Abstract
Advanced next generation communications technologies offer the potential to greatly improve safety, system efficiency, and mobility across our Nation's roadways. These new technologies and processes can address both traditionally difficult as well as entirely new challenges facing the transportation sector by expanding on available solutions, offering more sophisticated approaches, and creating new opportunities. This white paper explores Mobile Ad Hoc Networks (MANETs): a unique next-generation technology that can serve as a supplement or an alternative to traditional physical infrastructure-based wireless communications. MANETs are fluid, movable wireless networks that can form independently on an as-needed basis and do not require any fixed networking infrastructure to operate. As connectivity and communication become more vital to transportation needs, there is a tremendous opportunity for the use of MANETs in this field.

The goal of the white paper is to provide a background on how MANETs work and how they can potentially address the transportation needs of tomorrow. It begins by describing the current state of practice for MANETs and their current use in transportation applications. The paper also sets out to describe potential benefits and challenges associated with MANETs and offers potential transportation use-cases which justify further research into wider, transportation-based applications.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

5G	fifth generation of mobile technology
AODV	ad hoc on-demand distance vector
CIA	confidentiality, integrity, or availability
COTS	commercial off-the-shelf
DSA	dynamic spectrum access
DSR	dynamic source routing
DSRC	dedicated short range communication
DTN	delay/disruption tolerant network
EAR	Exploratory Advanced Research
FANET	flying ad hoc network
FHWA	Federal Highway Administration
HetNets	heterogeneous networks
IEEE	Institute of Electrical and Electronics Engineers
ITS	intelligent transportation system
IoT	internet of things
LTE	long term evolution
LTE-A	long term evolution – advanced
MANET	mobile ad hoc network
OLSR	optimized link state routing
OppNets	opportunistic networks
QoS	quality of service
UAV	unmanned aerial vehicle
USDOT	U.S. Department of Transportation
UWB	ultra wide band
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VANET	vehicular ad hoc network
WPAN	wireless personal area network

Executive Summary

Advanced next generation communications technologies offer the potential to greatly improve safety, system efficiency, and mobility across our Nation's roadways. These new technologies and processes can address both traditionally difficult as well as entirely new challenges facing the transportation sector by expanding on available solutions, offering more sophisticated approaches, and creating new opportunities. This white paper explores Mobile Ad Hoc Networks (MANETs): a unique next-generation technology that can serve as a supplement or an alternative to traditional physical infrastructure-based wireless communications. MANETs are fluid, movable wireless networks that can form independently on an as-needed basis and do not require any fixed networking infrastructure to operate, as seen in figure 1 below. As connectivity and communication become more vital to transportation needs, there is a tremendous opportunity for the use of MANETs in this field.

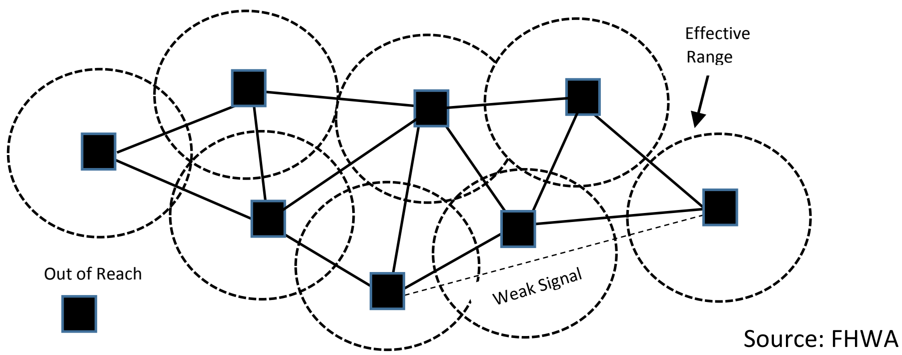

Figure 1. Illustration. Next-generation wireless communication environment: Non-fixed infrastructure MANET consisting of computers.

The goal of this white paper is to lay the groundwork for discussing a potential Government role in facilitating the development and application of MANETs in the surface transportation sector. It begins by describing the current state of practice for MANETs and their current use in transportation applications. The paper also sets out to describe potential benefits and challenges associated with MANETs and offers potential transportation use-cases. This white paper makes two key assumptions about MANETs and the next generation communications technologies that support them:

- They will have an impact on the transportation system. The Government is taking an active role at this time to shape this impact and identify potential challenges.
- They will offer compelling benefits above existing communications systems. There will be a role for Government-industry-academic partnerships to break through significant challenges.

There are many potential use-cases for MANETs to justify further research into wider, transportation-based applications. In an effort to catalyze and shape discussions about the potential Government role of MANET applications in transportation, the Federal Highway Administration (FHWA), during the summer and fall of 2017, supported a series of conversations and workshops with stakeholders across Federal, State, and local Governments. With this white paper and follow-up discussions, FHWA aims to provide a background on how MANETs work and how they can potentially address the transportation needs of tomorrow.

Introduction

Advanced, next-generation communications technologies offer the potential to greatly improve safety, system efficiency, and mobility on our Nation's roadways. However, significant adoption of mobile applications is likely to quickly exceed the design and capacity of existing wireless communications networks, limiting the potential mobility and safety benefits of these applications.

Mobile ad hoc networks (MANETs) are one of the potential solutions to this problem. A MANET is "a self-configuring network of mobile routers connected by wireless links with no access point."(1) While research on general-purpose MANETs—networks that have no infrastructure or specific intended application—is abundant,(2) potential applications of MANETs to the national transportation system have not advanced beyond small-scale research activities, such as traffic management for road segments in downtown areas(3) and intelligent traffic signal scheduling algorithms.(4) To explore further research and application of MANETs, FHWA's Exploratory Advanced Research (EAR) Program, which focuses on longer-term, higher-risk research with a high payoff potential, commissioned the production of a white paper on the state of the practice of MANETs. The focus of the paper is on the potential application of MANET concepts to surface transportation and the potential Government role in facilitating the development and application of MANETs in the transportation sector.

Technology Overview

MANETs are fluid, movable wireless networks that can form independently on an as-needed basis. The network is defined by mobile nodes (smart devices, vehicles with data-sharing capability, etc.) that receive and transmit data, and which require no fixed or dedicated infrastructure. This network paradigm lends itself well to fast moving, complex, and dynamic applications (e.g., Transportation Systems Management and Operations). Nodes can transition into and out of the network through physical movements or through devices turning on or off. The network can then reconfigure itself to accommodate these changes. Further, each node may also act as a conduit, sending and receiving information that may not directly concern its own operation.

The nodes in a MANET can communicate through a combination of existing wireless technologies—Bluetooth [IEEE802.15.1], Wireless Personal Area Network (WPAN),[1] Wi-Fi [IEEE 802.11],[2] 5.9 GHz Dedicated Short Range Communication (DSRC), Wireless Local Area Network,(2) Ultra-Wide Band (UWB), Worldwide Interoperability for Microwave Access, or ZigBee—a 802.15.4 standard low-power wireless network technology used for creating personal area networks [IEEE 802.15.4].(5) This use of multiple wireless protocols could allow nodes of different types (and manufacturers) to communicate seamlessly within a MANET and without any network infrastructure. When all participating nodes operate on the same frequency, use the same wireless technology, and use the same networking protocols, however, it is more likely that critical communications will be interoperable and conveyed with very low end-to-end latency.

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[1] WPAN is a very short-range network that consists of low power and low complexity wirelessly connected devices that operate in a personal operating space, which is usually within a radius of 10 meters or less. For more information, see: http://www.ieee802.org/15/pub/WPAN-FAQ.html. Accessed 4-7-17.

[2] IEEE 802.11 is a standard for wireless technology as determined by the IEEE Standards Association. 802.11 builds on the 802 standard but incorporates Wireless LAN Medium Access Control and Physical Layer (PHY) Specifications. For more information see: http://standards.ieee.org/about/get/802/802.11.html. Accessed 6-9-17.

Benefits

A MANET can serve many needs that traditional physical infrastructure-dependent networks cannot. For example, MANETs can provide cellular network offloading. Network offloading can be crucial in situations where the number of users on a network approaches or exceeds the network capacity, causing delays and other interruptions in service. MANETs are capable of temporarily diverting traffic from traditional network infrastructure to reestablish service for, or increase the number of, users within a typical area of coverage. In a similar light, MANETs are able to expand the coverage of a given network to regions beyond what an infrastructure-dependent network usually covers. MANETs can also provide communication and information dissemination capabilities in areas that temporarily or permanently lack an efficient communication infrastructure. Some examples where this might be the case are post-natural disasters areas, rural areas, areas with few economic resources, or areas with high degrees of inaccessibility, such as tunnels. Another potential benefit of MANETs is proximity-based applications. Several potential use-cases or applications of MANETs utilize the co-location of nodes to identify opportunities and provide services such as parking availability, which can result in environmental and social benefits.(6) Example MANET applications are described in detail in Appendix B.

Classes of MANETs

MANETs are a broad category of ad hoc networks. This category can be broken down into several subcategories, which encompass other types of ad hoc networks. Over the last five or so years, MANET research has shifted away from the pure general purpose paradigm towards more specific types of uses for MANETs.(2) Each type, some of which are further described below, has unique benefits and challenges for which new protocols must be used or created to fully utilize the application.

Vehicular Ad Hoc Networks

A vehicular ad hoc network (VANET) is a specialized mobile ad hoc network consisting of vehicle nodes that communicate wirelessly. The most prevalent means for this type of communication is via the Institute of Electrical and Electronics Engineers (IEEE) 802.11, or Wi-Fi, protocols.(7) Modern vehicles carry anywhere between 20 to 50 antennas, which facilitate communications within these channels.[3]

Unlike general purpose MANETs, VANETs are not restricted by typical mobile device battery limits because of their reliance on the built-in vehicle battery, which—in addition to having a much greater capacity than portable electronics batteries—can recharge as the vehicle is moving. VANETs are, however, usually constrained by road and other vehicle-specific characteristics.[4] Overall, VANETs exhibit a unique network topology when compared to MANETs. VANETs must accommodate more dynamic changes to the number and density of connected nodes, can span greater distances through a large fleet of vehicle nodes, and exhibit high mobility of nodes due to vehicle speeds. An increase in mobility intensity, which is a node that covers a large surface area, will generate more contact opportunities between nodes but also more limited opportunities for establishing and maintaining a connection.(8) When node density is high and too many radios try to access the spectrum simultaneously, VANETs may experience spectrum scarcity, meaning there is less available space for communication on wireless channels. In traditional infrastructure networks, such as cell phones and Long Term Evolution (LTE)/Long Term Evolution-Advanced (LTE-A),[5] this problem is minimized through synchronous communications

[3] Personal Interview with USDOT Subject Matter Expert, March 2017.
[4] This is not necessarily a limitation because restricted paths can lead to simpler routing protocols.
[5] Both of these standards use high spectrum flexibility and varying channel bandwidth for high speed wireless communication. For more information, see http://www.sciencedirect.com/science/book/9780123854896. Accessed 4-6-2017.

where a tower or central radio directs all other nodes when to schedule their transmissions. VANETs, and MANETs in general, transmit via asynchronous communications, which do not have that central authority.[9] One possible solution for addressing this issue is Dynamic Spectrum Access (DSA), which allows unlicensed users to access and take advantage of spectrum that are not being used, at the time, by licensed users.[2] While there have been many research efforts focused on DSA, there are no direct applications currently possible.[10,11] Some of the potential applications of VANETs include collision avoidance, road obstacle warning, and safety message disseminations.[11] Use-cases can be categorized by the scope of impact as seen in Appendix B.

Flying Ad Hoc Networks

Compared to VANETs and other surface MANETs, flying ad hoc networks (FANETs) are a relatively new and less explored form of MANETs that face even greater spatial challenges. FANETs generally consist of an ad hoc network between small, mobile unmanned aerial vehicle (UAV) nodes. Compared to existing UAVs that are much larger and use satellites to relay data to ground-based users, FANET UAVs have a much lower acquisition and maintenance cost, can cover larger dynamic areas at any given moment, and their ability to relay information or form a network is not dependent on any single node.[12] Compared to VANETs, average distances between FANET nodes tend to be much larger. Moreover, while propagation issues caused by buildings and terrain can be less problematic for FANETs, establishing and maintaining a link between each node may require different radio links, hardware circuits, sensors, and mobility handling capabilities caused by the large distances.[12]

Because of the 3-D nature of their movement and the speed of nodes flying in varying directions, typical solutions and standards for VANETs are not always applicable to FANETs. For example, while end-to-end routes can be used for VANETs, continuous yet typical topology changes can create significant delays or route failures, especially when transmitting data packets such as multimedia files. Existing VANET routing protocols, such as dynamic source routing (DSR),[6] ad hoc on-demand distance vector (AODV) routing,[7] and optimized link state routing (OLSR)[8] are also not ideal for the packet forwarding in this scenario. Some research suggests that this type of issue can be solved with beaconless opportunistic routing protocols, which minimize packet transmission loss by identifying relay nodes to forward packets, and more easily recovering from route failures.[13] Similar to VANETs, FANETs also have battery capacity limits related to how much weight a FANET node can carry. FANETs also must consider collision avoidance mechanisms. In one example, the National Aeronautics and Space Administration has explored field tests using DSRC within unmanned aircraft systems to support tactical separation among nodes.[9]

Some possible applications of FANETs in transportation are uninterrupted live video sequences of traffic and other related safety incidents, general traffic monitoring, and natural disaster event response. FANETs can also provide internet access to infrastructure-poor regions through floating or orbital nodes. Google's Project Loon and Facebook's Internet.org provide LTE-equipped floating balloons and solar-powered drones, respectively, with the intent of creating a mobile flying cellular infrastructure. Additionally, other projects, such as SpaceX and OneWeb, hope to provide lower orbit satellites that can create end-to-end communications. While floating applications have demonstrated initial success,

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[6] A reactive routing protocol that computes routes as necessary, not periodically, and then maintains them.

[7] A low network-utilizing reactive protocol that, like DSR, computes routes as necessary and maintains them but also uses destination sequence number delivered from the route sender node.

[8] A proactive routing protocol that constantly sends topological information to all available network nodes and continuously maintains routes. For more information on each of these three protocols, see: Narsimaha, V.B. (2012).

[9] National Aeronautics and Space Administration, Ames Research Center (July 2017). Meeting Presentation.

orbital applications have not yet been implemented.[6] Transportation-related communications may have the potential to exploit these types of networks if needed.

MANET Class Variations

As research has advanced, there have been improvements to how each MANET application operates independently and with other networks. These improvements include better routing protocols, efficient end-to-end service, and more.

Opportunistic Networks

Opportunistic Networks (OppNets), derive from MANETs and delay/disruption tolerant network (DTN) topologies, which use technologies to address communication delays or complete disruptions. OppNets can arise as a result of a network's dynamically changing topology. While OppNets are not restricted to mobile nodes, their use of a "store-carry-and-forward" paradigm lends them particularly well to distributing data to and from portable devices, such as smartphones.[2] However, OppNets are not implemented widely, and the current research in this field is relatively immature as compared with other network technologies. Other reasons for this lack of adoption include lack of incentive from mobile operators to share or relinquish control over some of their fixed networks,[6] and prohibitive battery consumption for nodes that are in constant signal search mode.[14]

Heterogeneous Networks

Heterogeneous Networks (HetNets) refer to the deployment of different radio access technologies that create a network using diverse capabilities such as varying bit rates and range. The goal of a HetNet is to acquire optimal use of spectrum bands and energy through heterogeneous nodes.[2] While MANETs consist of spatially dynamic nodes, HetNets can consist of non-fixed and fixed nodes. In some application tests, fixed and non-fixed heterogeneous applications, such as vehicle-to-infrastructure (V2I) VANETs, demonstrate lower end-to-end communication delays and higher throughput performance.[7] This concept lends itself well to transportation applications since HetNets are constantly evolving and would benefit from access to different technology solutions.

Internet of Things

MANETs have a direct correlation with the emerging technology of Internet of Things (IoT). The IoT describes an interconnected network of physical objects (e.g., buildings, vehicles, and devices) that can collect, share, and exchange data. This system allows for better incorporation of the physical world into computer-based systems. Any object within the IoT that moves (vehicles and smart devices as an example) could work as a node in a MANET. Further, many IoT applications may rely on the use of MANETs. IoT application can also rely on machine-to-machine communication protocols.

Technology Landscape Assessment

Current Applications

As of 2016, research on MANETs has not been widely adopted or applied in the civilian wireless networking field. However, MANETs have had an important presence in two fields: military and disaster recovery.[2] In many situations, a military deployment involves operating a technology in harsh, infrastructure-less, and potentially hostile environments in which safe, reliable, and efficient communication is a challenge. For over a decade, military tactical units have used MANETs for autonomous maneuvering of unmanned vehicles and robots,(15) and for critical radio communications to provide timely situational awareness for current and upcoming operation phases and to maintain data and connection integrity.[10] In most cases, the military uses a combination of networks, including cognitive radio and satellites. The military will typically use more sophisticated nodes compared to commercial off-the-shelf (COTS) nodes that are commonly used elsewhere.(16) Following the example of the military, police forces have recently started using tactical MANETs for crowd management and surveillance. One example of the use of a tactical MANET was during the 2016 Boston Marathon to provide secure communication support to law enforcement up to 30 miles apart.[11]

As with military environments, disaster recovery environments are ideally served by MANETs because of their lack of infrastructure, topological barriers—such as collapsed tunnels—and potentially hazardous conditions.(17) Some of the primary concerns for disaster recovery applications include accurately predicting movements among nodes to locate team members and the fast delivery of emergency messages.(18)

Improvements to Current Wireless Technologies

As research on MANET applications develops, the wireless technologies underpinning MANETs also improve. On the physical layer, improvements include more advanced nodes, such as lighter and faster drones, more powerful and efficient smart phones, and overall more durable devices. Additionally, improvements in battery technology have allowed all types of devices to establish and maintain a network over a longer duration. Sensors within each device, such as more efficient accelerometers and wireless receivers within smart phones, have greatly improved over the past 10 years.

In addition to changes in sensors and nodes, major strides have been made in the efficiency, quantity, and quality of data transmission between nodes, as well as securing the data in transmission. With respect to vehicles, DSRC has become the standard for communication among vehicles, particularly in vehicle-to-everything (V2X) communications. DSRC is a one-way or two-way short-range to medium-range wireless communication channel. This type of medium was primarily designed for vehicular communication systems and can be seen in V2X-types of communications. Along with other wireless communication technologies, DSRC is used in intelligent transportation systems (ITS) to ensure safe and interoperable connectivity across all transportation system modes,[12] although to date most development has been concentrated on automobiles. While open to device manufacturers, application developers, and other users, safety applications are given priority over other applications.[13]

Overall, there is a low latency—the delay in node-to-node communication—during communication exchanges using DSRC. DSRC channels have a high level of interoperability with common standards adopted by manufactures, including some level of safety message authentication and privacy.[14] Because of this, DSRC is a potential medium for forming VANETs. Currently, however, DSRC is used mainly to broadcast information for crash avoidance purposes in the United States, which represents a precursor to a full MANET capability. Although multi-hop capabilities are included in Cooperative Intelligent Transport Systems standards for vehicle-to-vehicle (V2V) and V2I in Europe, this capability has not yet been widely developed in the United States. This means that for the United States, adoption of DSRC for

[10] https://www.trellisware.com/wp-content/uploads/2017/02/TW-225-01-CheetahNet-Mini-Datasheet.pdf. Last Accessed 10-5-17.

[11] Workshop Discussion with U.S. Navy Subject Matter Expert, October 2017.

[12] For more information, see: https://www.its.dot.gov/factsheets/dsrc_factsheet.htm. Accessed 7-3-17.

[13] Personal Interview with USDOT Subject Matter Expert, March 2017.

[14] Ibid.

MANETs will require further development of multi-hop capabilities.[15] Researchers and practitioners have discussed using "epidemic distribution" to distribute digital credentials and certificate revocation lists, which would make DSRC channels part of the MANET paradigm.

One of the most prevalent improvements in wireless standards is the fifth generation of mobile technology (5G), which builds on all previous generations (1, 2, 3, and 4), LTE/LTE-A, and other Radio Access Technologies.[(19)] 5G aims to be a HetNet that joins LTE to other wireless networks as a single system.[16] Among other characteristics, 5G technology combines existing technology to support operations on smaller wavelength (millimeter waves) spectrums with a higher bandwidth that can potentially produce data rates of tens of megabits per second for tens of thousands of users.[(19)] This next generation wireless technology is expected to provide a higher reliability, lower latency, and better address scalability issues when compared to previous standards. The degree to which 5G achieves each of these goals, however, remains to be seen. Researchers familiar with the technology argue that, in practice, only one or two of these targets can be achieved at once. For example, to achieve higher reliability at an extremely large scale, users must sacrifice latency. Thus, having both low latency and high reliability is not practical at a relatively large scale.[17]

Multiple public and private organizations are working together to develop 5G standards to serve a wide range of applications. Because of the number of collaborating groups and level of complexity for the new technology, 5G standards are not expected to be adopted until 2020 or beyond. Once completed, 5G is expected to address many challenges, including network heterogeneity, which consists of, among other things, the melding of 802.11-based radio access technologies such as Wi-Fi and DSRC, and varying current and evolving technologies, such as LTE.

Some of the potential applications for 5G technology include improved data communication on high-speed trains; improved three dimensional connectivity among aircraft, such as drones (FANETs); and automated traffic control and driving. Overall, the examples mentioned here are not meant to be exhaustive but rather a glimpse into 5G opportunities.

Limitations, Challenges, and the Federal Role

Two decades of research into MANET technology has resulted in a deep understanding of the field's strengths and limitations, along with the creation of numerous COTS products that can be used to create a MANET. While there has been limited Government application, new research shows potential adoption in fields such as industrial networks, smart grids, and ITS.[(2)] However, there remain technical and policy-related challenges to the technology's adoption and implementation.

Technical Challenges

Device interoperability through network standardization is critical for the wider adoption and adequate market diversification of MANETs.[(2)] In addition to standards and interoperability, performance optimization can be a significant challenge for MANETs. The ability to efficiently communicate between nodes through optimal routing protocols is complicated by the potential for propagation issues, such as multipath and background noise. As researchers and developers address these challenges, scalability has become more important and could be a barrier to further MANET adoption. Simply adding more nodes to a network will not create a highly functional MANET. Increased traffic density in a network can

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[15] For more information, see: http://local.iteris.com/cvria/html/applications/app2.html#tab-3. Accessed 8-25-17.
[16] Personal Interview with USDOT Subject Matter Expert, March 2017.
[17] Ibid.

lead to a broadcast storm problem, where node density above a certain value results in increased packet collisions.[20]

MANETs are also limited in their ability to provide Quality of Service (QoS)—the ability of a node or router to classify and transmit incoming data in a manner that matches rules or behaviors particular to the application that created the data.[18] In general, mobile wireless networks are prone to smaller and more variable capacity than wired networks, resulting in high data loss rates and weak QoS. In some cases, MANETs use media access control layers, which have little to no QoS support. Recent research projects have started addressing QoS loss but have seen limited results.[21] Further, while battery technologies improve in both capacity and efficiency in weight and size, integrating batteries and optimizing battery-use within MANETs continues to be a challenge by limiting network range, run-time, and node mobility.

Policy Challenges

Because MANETs have an infrastructure-free design, their adoption could be seen as a potential threat by more infrastructure-dependent mobile operators.[6] While this issue might not arise in areas where there is no existing infrastructure, conflict may arise in areas dependent on physical infrastructure. Creating a clear business-case for adoption by mobile phone carriers may ease any conflicts.

While MANETs could allow for significant benefits in safety, efficiency, and mobility, they may lead to significant risks regarding data confidentiality, integrity, or availability (CIA). Confidentiality concerns the level of access users have to data on a network; integrity concerns the legitimacy and accuracy of data; availability concerns how users can access data on the network.[22] One of the most impactful risks that includes all CIA elements involving MANETs is network security. At a network-wide level, MANETs create a constantly changing environment that can require fast authentication protocols, limited physical node security, and vulnerable channels of information that can be eavesdropped on or interfered with.[21] A vulnerable network is susceptible to security attacks that can replicate, modify, or delete data exchanged between nodes. For example, a malicious node can tamper a routing protocol by modifying route information to an unwanted node or by ending the route prematurely. Network security is particularly concerning when there are high-speed physical nodes in a MANET. While there are some common privacy and safety elements that can be used in MANETs, such as Elliptic Curve Cryptography, Public Key Infrastructures, and Digital Certificates,[23] there are still technical and privacy issues that are not fully addressed by existing solutions.

A performance evaluation gap exists for each type of application, especially as scalability becomes a concern. One role that the Federal Government can play is to identify feasible transportation MANET applications and promote the creation of realistic simulation models for diverse scenarios and real testbeds for experimental evaluation. Overall, interest is growing in mixed-network adaptations, centered primarily on HetNets.

One of the Government's current activities in MANETs, which is led by the U.S. Federal Communications Commission, focuses on spectrum band management for DSRC deployment; that is, determining which groups can have access to the network, and how much traffic these groups create. The Government has stimulated the development of standards for DSRC by creating a reference implementation model that is being merged with the ITS architecture. In addition, the Government has funded initial certification

[18] For more information, see: http://www.juniper.net/techpubs/en_US/learn-about/LA_QoS.pdf. Accessed on 4-20-17.

efforts to ensure interoperability and security. With 75 MHz of spectrum dedicated primarily to DSRC,[19] there is potential for the USDOT to further develop and apply MANET standards and technologies in the connected vehicle field. This would require more agreement on the transmission of interoperable data, without which there is little incentive to create and deploy the physical media necessary to transmit and receive these data. For example, during the development of a crash avoidance technology using DSRC, much time was consumed by getting all parties to agree on a data unit to share. There is a great opportunity to better coordinate among relevant stakeholders and use the 75 MHz of spectrum for further innovative developments in transportation safety and efficiency.

Outside of Government, there are other organizations that address wireless standards and interoperability, which the Government can collaborate with. The Wi-Fi Alliance, for example, is a consortium of companies and contributors that certify new technologies that effectively use 802.11 standards, in both 2.4 and 5 GHz.[20] Additionally, IEEE is a professional association that created the 802 standards for wireless technologies. IEEE consists of over 400,000 engineers, scientists, and allied professionals worldwide who contribute to over 1,300 international technological standards.[21]

Summary

Technological advancements in wireless networks could lead to significant improvements in mobility. However, work still needs to be done to explore how these networks could be used in the transportation system safely and efficiently. Additionally, these networks must serve the public interest, particularly in areas such as safety, security, and policy. There is a potential Federal Government role in coordinating technological advancements in the use of wireless communication protocols for transportation applications by promoting targeted applications, such as using drones for bridge inspections, to monitor traffic in disasters, and backup transportation-related communications. These applications must address vital transportation needs that are not currently fully met and therefore merit further Government investment.

[19] There are other primary users in this spectrum range, and co-existence arrangements have been negotiated for DSRC and satellite uplinks, for example. Other uses such as industrial, scientific, and medical services also overlap the DSRC spectrum.
[20] For more information, see: http://www.wi-fi.org/certification. Accessed on 4-7-17.
[21] For more information see: http://www.ieee.org/about/today/at_a_glance.html. Accessed on 4-7-17.

Appendix A. About the EAR Program

FHWA's EAR Program is intended to spur innovation and focus on higher risk and higher pay-off research. Exploratory Advanced Research bridges basic and applied research. In contrast to basic research, EAR Program-funded research projects have a mission orientation. In contrast to applied research, EAR Program-funded research does not pursue a narrowly defined application or product. Incremental advances and demonstrations or evaluations of existing technologies are not within the scope of this program.

The EAR Program seeks to fund research projects that could lead to transformational changes and truly revolutionary advances in highway engineering and intermodal surface transportation in the United States. It supports scientific investigations and studies to advance the current knowledge and state-of-the-art in the sciences and technologies employed in the planning, design, construction, operation, maintenance, and management of the Nation's highways. Strategically, this research will enable and expedite the development of revolutionary approaches, methodologies, and breakthroughs required to drive innovation and greatly improve the efficiency of highway transportation.

Appendix B. MANET Use-Cases

FHWA's EAR Program is currently exploring MANETs and their application to surface transportation. As part of that consideration, FHWA is exploring potential use-cases for MANETs in transportation.

Potential applications for MANETs cross a variety of transportation foci. Operational efficiency management is one of the most common applications of MANETs, as it can encompass a wide variety of simple and complex day-to-day tasks, including traffic management or routing for any mode of transportation. Safety applications of MANETs can be critical in ensuring efficient use of transportation systems to deliver emergency services and security where current infrastructure is lacking. MANETs may have applications specific to urban environments, as well as others most appropriate for rural or remote settings. These use-cases cover the deployment of MANETs as either a primary or secondary communications capacity. The following categories and subsequent use-cases are meant to be examples of potential MANET applications and not exhaustive of existing or nonexisting applications.

a) **Operations (Urban)**: MANETs may be deployed in high traffic density areas with limited cellular signal strength, such as a subterranean interstate highway through a major urban region (e.g., Boston's "Big Dig" I-93 tunnel). Additionally, there are potential applications in environments featuring viaducts over roadways (i.e., Wacker Drive in Chicago). These types of densely structured and populated urban environments support MANET applications for traffic management, including advanced incident warning, rerouting information, or speed management. In this capacity, MANETs have the potential to expand on connected vehicle infrastructure or vehicle-based pilot deployments (e.g., in New York City) if available. MANETs might also be used to carry multiple video feeds in disaster situations, which could prove beneficial to traffic managers and improving overall situational awareness. MANETs here are not only an extension of fixed communications infrastructure but can serve as a secondary resource for failures in the design of the limited infrastructure or V2V and V2I environments.

b) **Information Sharing/Evacuation**: MANETs may be applied for pedestrian wayfinding, routing, tracking, and information sharing in situations with a high density of people but limited radio signal access. Two potential examples include an underground transit station or a large arena or stadium hosting an event with a large crowd. MANETs may be able to interface with existing tactical radios used by first responders and public safety personnel for additional coverage. For each case, MANETs could be both primary and secondary networks that provide routing opportunities for areas that are over capacitated or do not have any network service to begin with.

c) **Intersection Management:** MANETs may be applied on crowded and dangerous intersections to protect vulnerable users (e.g., pedestrians and cyclists), with the goal of guaranteeing their safety. In particular, a MANET formed by vehicles and infrastructure installed on the intersection, can prevent accidents by protecting users from potentially dangerous vehicles in an automated fashion. The MANET collaborative localizes and tracks vulnerable users and helps to adjust the speed and trajectories of vehicles based on user positions.

d) **Freight**: MANETs may be applied to facilitate movement in high density, multi-modal freight facilities. Through communication between closely coupled nodes in small areas, nodes can route vehicles through these tight or crowded spaces to improve efficiency of freight operations. For example, MANETs could serve as a bridge for maintaining a continuous connection between nodes when there are temporary failures in other primary networks while communicating localization and routing information. MANETs incorporating UAVs for video transmission could provide additional functionality in this application.

e) **Incident Management**: MANETs may assist in the location of individual cars and people via mobile devices when cell towers are inaccessible or malfunctioning. This application may be particularly useful in more rural and remote environments that currently experience slower emergency response times.

f) **Operations**: MANETs may be used to help coordinate and assemble vehicle platoons, which can result in better fuel economy and reduced congestion. The networks can assist in freight movement and heavy truck platooning along major corridors, which can also result in increased economic benefits.

g) **Mobility/Routing (Rural)**: The use of MANETs in National Parks or similar areas with limited wireless communications infrastructure may be applied to shuttle services that operate to and within each park. MANETs could assist in the deployment of traditional or automated shuttles and provide important schedule, trip, and other related announcements to the Parks' users. MANETs could also provide trip scheduling and traveler guidance for areas with limited radio signals.

h) **Mobility/Routing (Urban):** The use of MANETs for large-scale events (e.g., Presidential inaugurations, outdoor music festivals, and sporting events) may be applied to transportation services in and around these events. MANETs could assist in the deployment of traditional or automated shuttles and provide important schedule, trip, and other related announcements to event participants.

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