# SSDNet: Small-World Super-Dense Device-to-Device Wireless Networks

Wei Cheng, Jiguo Yu, Feng Zhao, Xiuzhen Cheng


## Abstract

In this article, we propose a novel networking paradigm called Small-world SSDNet, servicing applications such as public safety, proximity based services, and fog computing based on device-to-device multi-hop wireless communications. The "small-world" feature is determined by the service area, whose size is usually within a community level, and the well known small-world properties existing in SSDNets; the "super-dense" feature comes from the fact that the increased direct communication range and the popularity of 5G and IoT devices jointly result in a large number of devices within a single-hop communication range. This article first formally defines SSDNet. Then the challenges and the opportunities brought by the design and the implementation of the SSDNet protocols and applications are addressed. Finally, the broader discussions on issues relevant to modeling, engineering, and dissemination are provided.


## Model and Key Features

A Small-World Super-Dense Device-to-Device wireless Network (SSDNet) is a novel distributed system with a small network radius (two to four hops) and a large number of users within a single-hop communication range. The devices in a SSDNet are heterogeneous in terms of computational power, communication capability, and owner's preferences. Figure 1 summarizes the key features of SSDNets and their impacts on the designs of the corresponding layers.

SSDNets target on serving the applications, most of whose communication and networking activities are within small areas. Though the era of IoT (Internet of Things) has pushed everything to the Internet, researchers have pointed out that this model is not necessary and/or inappropriate for many applications such as fog/edge computing, which is one of the SSDNets served areas.

The "small-world" term comes from the fact that the mathematical graphs formed by SSDNets devices are small-world networks, where the hop distance between any two devices is upper bounded by a small positive number such as 5. The "small-world" feature of an SSDNet is essential because of the application requirements, the availability of the resources, the complexity in computing, the performance in implementations, the requirements in management, and the business barriers. The size of a community, usually a couple of blocks or less, could be perfect for SSDNet applications.

In addition to the well known small-world properties, "small-world" in SSDNets further implies lightly-weighted considerations on scalability, easier in scheduling, and less end-to-end delay, which jointly reduce the difficulties in the design and implementation at the application layer, network layer, and management.

The "super-dense" feature of a SSDNet is obvious. The European METIS project predicts that 5G will have 10 times to 100 times higher number of connected devices by 2020, approximately 200,000 devices per km$^2$. The experiments conducted in Bonn demonstrated that the peer discovery range of LTE Direct at the 2.6 GHz band varies from 65 m to 550 m. Specifically, the peer discovery range of rural LOS (line of sight) is 550 m, that of urban LOS is 350 m, that of urban NLOS (non-line of sight) is 170 m, that of indoor is 140 m, and that for two peers with one in deep indoor and the other in outdoor is 65 m. Correspondingly, there will be up to 2,650 to 190,000 devices within a device's direct discovery range. Though this number may be much smaller in the near future, it can still reach "hundreds" within a one-hop range. Users in a SSDNet, therefore, are indeed super dense (with a super large node degree). In addition, the number of active users that have concurrent transmission demands may also be large. For instance, public safety applications might have continuous burst traffic right after the occurrences of disastrous events. This "super-dense" feature brings additional competition for spectrum access in the physical and link layers, a near complete graph as the single-hop topology in the network layer, and more challenging management tasks for the operators.

SSDNet devices are heterogeneous. They could be user equipment, first responder devices, IoT devices, community fog servers, wireless relays, home fog hubs and network monitors, just to name a few. These devices are able to communicate with each other, but their communication and networking functionality varies with the hardware platforms, the installed software packages, and the implemented standard versions. Additionally, the owners should have their own controls on how to utilize the devices for multi-hop communications at the network and application layers.

This article is organized as follows. The following section presents the motivation for proposing SSDNet and the lineage of SSDNet related technologies. Then we summarize the challenges and opportunities brought by the design and implementation of SSDNet protocols and applications. Broader discussions on issues related to modeling, engineering, and dissemination are then presented, followed by a conclusion.

*Wei Cheng is with The Virginia Commonwealth University.*

*Jiguo Yu is with The Qufu Normal University.*

*Feng Zhao is with The Guilin University of Electronic Technology.*

*Xiuzhen Cheng is with The George Washington University.*

Digital Object Identifier: 10.1109/MNET.2017.1700086

## Motivation and Lineage

### Motivation

SSDNet provides a new networking paradigm whose emerging momentum is jointly determined by the availability of the current and future technologies as well as the needs of new applications, as illustrated in Fig. 2.

Public safety, proximity based services, and fog/edge computing are three foreseen application areas whose needs are the primary motivations behind the emergence of SSDNets. The National Institute of Standards and Technology (NIST) states that the direct mode operation is a life line for first responders, which allows them to communicate independent of existing network infrastructures. First responders should be able to communicate with and locate the people holding public safety enabled devices in emergencies when infrastructure based services are unavailable. For example, after earthquakes, infrastructures may be down and people usually have bursty demands for sending messages to first responders. It is, therefore, essential to have robust device-to-device (D2D) communication and networking platforms for small-area (such as a first responder's service area) public safety applications that may have a large number of users.

Proximity based services provide a variety of information sharing functions such as indoor way-finding, proximity based advertisements, and D2D direct chats, for nearby users within a small area. 3GPP (3rd Generation Partnership Project) began to release LTE specifications under the label Proximity Services (ProSe) in 2013. As GPS, WiFi, and the Internet may not be available in public indoor environments such as a convention center, D2D based communication, localization, and networking systems will be the essential means serving a massive number of users. For example, big events usually have hundreds of participants within each other's D2D communication range. They have the need to communicate with and find unknown particular users under the environment where location and Internet services may be unavailable.

Fog/edge computing is an emerging area that targets providing services to the customers within a community-level IoT (Internet of Things). It intends to offer less economic cost, more efficient transmissions, stronger data security/privacy protection, and more trustable administration than the traditional cloud based services. For example, the transmissions of sensitive data shared among local users should not rely on the Internet-based cloud services, which may be more insecure, slower, and more expensive. D2D based data transmissions can be the key technology for finding solutions to meet the customers' needs and promote killer applications in fog computing. With the popularity of IoT devices, the study of D2D communications and networking for a large number of users within a community will therefore be a must.

One can see that all three impetus applications require the support of D2D communication and networking technologies for a large number of users in a small area. Furthermore, as a single hop discovery/communication range has reached up to 500 meters, the problems to be resolved are

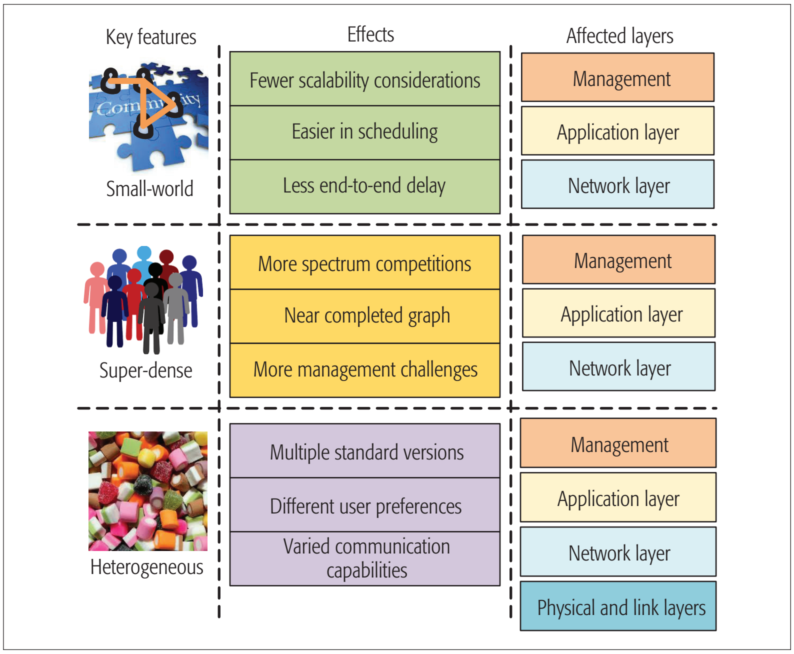


FIGURE 1. SSDNet features.

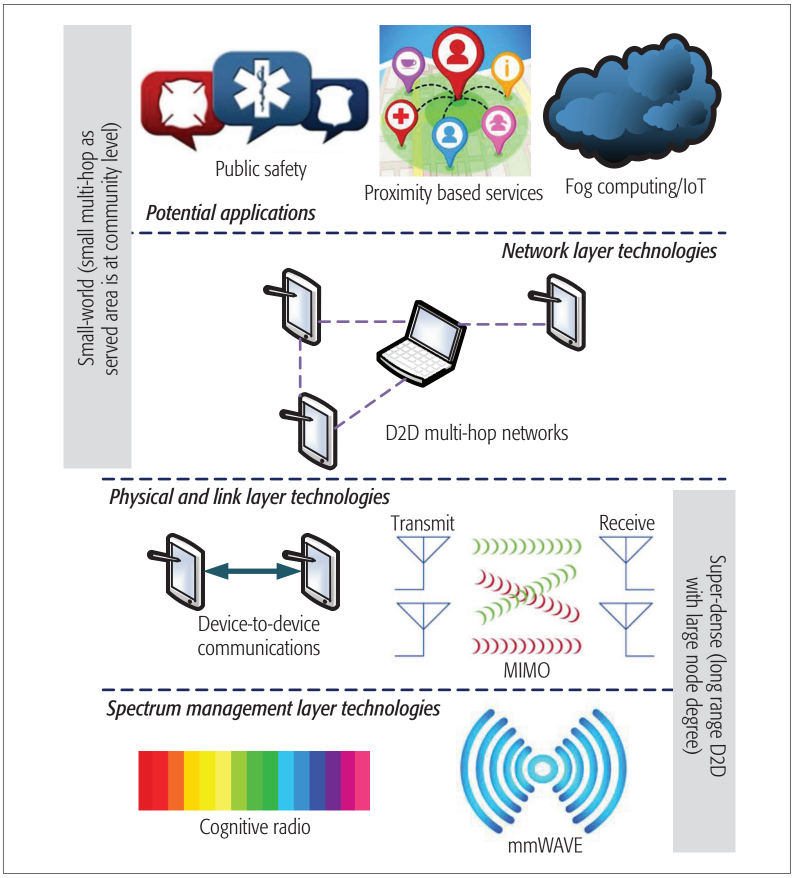


FIGURE 2. SSDNet technologies and example applications.

shifted to the new context that comes out as a special D2D heterogeneous wireless network, whose hop based radius is small (Small-World) while the number of direct neighbors is large (Super-Dense).

| | MANET | SSDNet |
|---|---|---|
| Management | Infeasible for conducting traffic monitoring, security control, privacy protection, and trust management. | Feasible; application based sub-network topology control. |
| Application layer | Usually one network for one application, usually non-heavy traffic. | One network for multiple applications; hybrid traffic; more impacts on lower-layer design. |
| Network layer | Heavy scalable routing; whole network topology control; high cost for supporting mobility. | Simple and effective routing; application priority based routing; light or moderate cost for supporting mobility. |
| Physical and link layers | Time-division multiplexing; collision avoidance; low or moderate competition. | Time synchronized; application pattern based; high competition (super-dense). |

TABLE 1. The differences between SSDNet and MANET.

## Lineage

Technically, the emergence and success of SSDNets are based on the available and future developments of the technologies in D2D communications, MIMO, non-orthogonal multiple access, cognitive radios, and mmWave. Each of these fields has been extensively studied in recent years within contexts other than SSDNets, which however brings new challenges and opportunities.

SSDNet inherits from MANETs (mobile ad-hoc networks) the key concepts of D2D communications and multi-hop ad-hoc networking. However, SSDNet based solutions should be radically different from those in MANETs in many aspects.

The studies of ad-hoc networking technologies [1] have addressed the problems at each layer of the protocol stack for building a self-organizing wireless network, but unfortunately the network radius is largely ignored, whose critical role in facilitating the more efficient designs of routing and topology control however has been recently recognized. Moreover, the current ad-hoc network applications (such as sensor networks) are based on non-super-dense networks, where the node degree is usually ≤ 10 in real world applications and ≤ 30 in research settings. In a SSDNet, within the radius of 500 meters, the node degree can easily reach hundreds, rendering the existing MANET MAC, routing, and topology control protocols disqualified. Table 1 summarizes the main differences between MANET and SSDNet. More details regarding the research challenges and opportunities will be discussed below.

Due to the supper-dense feature, it is obvious that the licensed and the ISM (Industry, Science, and Medical) wavebands are insufficient to simultaneously service hundreds of active mutually interfering users. Similarly, LTE base stations and MIMO WiFi access points usually can serve at most ≤ 100 active users in reality. It is, therefore, essential to employ spectrum management techniques such as CR (cognitive radio) [2] and mmWaves (millimeter wave) [3] to enhance spectrum utilization. CR allows unlicensed users (secondary user) to utilize a licensed band when the licensed users (primary users) are not active, while mmWaves extends the communication spectrum up to the 300 GHz band. On the other hand, non-orthogonal spectrum multiple access technologies (such as the ones in power domain and code based) can also contribute to increasing spectrum utilization efficiency.

D2D technologies provide basic one-hop communications. Similar to the problems encountered by ad-hoc networking, most existing D2D communication technologies [4] may not work in a super-dense environment. ProSe defines one-to-many and one-to-one UE (user equipment) direct communications in layer-2 in the corresponding 3GPP specifications. The manufacturers have their ProSe solutions evaluated in the simulation/deployment environments with ≤ 25 active UEs. LTE Direct (standardized as part of ProSe) is a one-to-many communication solution under the standardization in R-12. It is synchronized and only targets short message transmissions. To our best knowledge, there is still no commercialized ProSe-enabled products for public safety applications. Therefore, D2D needs to be carefully studied for conceptual and practical SSDNet applications.

Note that the concept of "super-dense" in SSDNet is totally different from the one termed "ultra-dense" in UDNs (ultra dense networks) [5]. "Ultra-dense" means dense cells (≥ $10^3$ cells/km$^2$) while SSDNet means exactly the opposite side. UDN is infrastructure based while SSDNet is not. DSRC (dedicated short range communications) for vehicular networking (VANETs) also creates "small-world" application scenarios, but it is not that "super-dense." SSDNets' networking technologies may be applied to VANETs after adding the modifications to handle more mobilities. Body sensor networks (BSN) are very small scale networks. Multiple BSNs may interfere each other [6] and yield super dense contexts with the specific channel characteristics near human bodies. In SSDNets, a BSN may be treated as a single BSN-device that has intra-communication interferences to other BSN-devices and D2D-communication interferences to SSDNet devices. Wireless mesh networks [7] have the most overlapping application areas with SSDNets, but they rely more on mesh infrastructures (such as mesh routers and gateways) with limited considerations on "super-dense" and "small-world." SSDNets and wireless mesh networks complement each other. Named data networks (NDN) name data instead of their addresses. As NDNs' applications may first emerge in the edges (small area and dense IoT deployment), SSDNet will have the opportunity to provide efficient services to NDN for caching, routing, and security.

## Research Challenges and Opportunities

No one can ignore the momentum of SSDNet's growth as it is essential for a series of emerging killer applications that will eventually become mature and popular. This section enumerates SSDNet's challenges and opportunities in the physical and link layers, network layer, application layer, and management. Table 2 summarizes the research challenges and opportunities in SSDNet with the corresponding performance indicators.

### Physical and Link Layers

**D2D Intra-Interference:** The difficulty level in the design of the physical and link layers for SSDNet is very high because of the challenges pre-

| | Challenges | Opportunites | Performance indicators (include, but are not limited to) |
|---|---|---|---|
| Management | Access control; privacy protection; trust management; real-time topology control. | Small-world makes traffic monitoring possible, trust management feasible, and subnetwork topology maintenance easier. | UE trust Level; information leakage; intrusion detection rate and respond time. |
| Application layer | Cross layer design; quick localization; energy saving/sharing; heterogeneous applications. | Small-world provides more opportunities to optimize applications for channel allocation and routing; super-dense increases the success rate of ad-hoc localization. | Location accuracy; location time; energy consumption; one time. |
| Network layer | Efficient and quick routing; varied UE routing policies; heterogeneous networking; capabilities and functionalities. | Super-dense increases the success rate of route discovery; small-world provides the opportunities to design non-flooding based efficient routing algorithms, and utilize route cache. | Route discovery success ratio; route discovery delay; delivery ratio; data rate; latency; overhead; traffic balance; robustness; and stability. |
| Physical and link layers | Interference management; interference cancellation; quick peer discovery; media access and scheduling; D2D range control; broadcast and multicast. | Time synchronized devices make the scheduling design easier; small-world brings the possibility of traffic pattern based scheduling. | Communication range; data rate; energy consumption; maximal capacity; delays in discovery and communications; interferences to other wireless communications; discover ratio. |

TABLE 2. Research challenges and opportunities in SSDNets.

sented by the "super-dense" feature and the fact that the number of active users may reach several hundreds within a one-hop communication range. Generally, 100 is greater than the threshold of the number of active users associated with a WiFi access point or a cellular station (max 100 available PRBs, which is the smallest unit of bandwidth assigned by the base station scheduler, in LTE) [8]. CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) based IEEE 802.11 protocols, which are used in WiFi Direct for D2D communications, and OFDMA (Orthogonal Frequency Division Multiple Access) and SC-FDMA (Frequency Division Multiple Access) based 4G cellular communication protocols are not the solutions for SSDNet's physical and link layers. Non-orthogonal spectrum multiple access technologies could be favorable, but still need further investigation.

**Typical D2D Technology:** D2D technologies have been extensively studied in LTE networks [9–11]. LTE Direct is a solution running on licensed spectrum for ProSe one-to-many communications. Each LTE Direct device can use either uplink resources (≤ 1 percent) in LTE FDD systems or dedicated frames in LTE TDD systems to broadcast up to 2,816 expressions (short messages, 128 bits each). In the future Release 14, which is expected to be released in 2019, LTE Direct will add the feature of multi-hop communications. Note that LTE Direct is still constrained by the licensed spectrum and thus is not a mature solution for super-dense D2D.

**Interference to Non-D2D Communications:** D2D should not affect or degrade other wireless communications. The D2D communication technologies surveyed in [4, 12] have addressed the problems regarding how to utilize CR and how to minimize D2D interference to WiFi and cellular. However, they are still not natively designed for a super-dense environment.

**Broadcast and Multicast:** Broadcast and multicast are efficient information sharing mechanisms among UEs. In LTE eMBMS (evolved Multimedia Broadcast Multicast Services), base stations aggregate downlink resources from the UEs that request the same content such as live streaming video for multicast so that those UEs' overall throughput and spectrum efficiency can be increased. However, LTE eMBMS is based on infrastructures such as MBMS Gateway and is controlled by operators. As a result, LTE eMBMS may be unavailable for SSDNet applications in public safety applications. The studies of D2D multi-hop multicast are therefore essential. Moreover, requirements such as real-time scheduling, QoS, priority, and preemption from SSDNet applications are still not addressed in the multicast literature. The small-world feature will provide an opportunity to efficiently design multicast solutions.

**D2D Communication Range:** D2D communication range plays an important role in SSDNets. If it is too small, the network hop radius can be significantly increased, resulting in increases in networking complexity, end-to-end delay, and possible failure of applications. For example, localization in public safety applications may fail due to an insufficient number of UEs within a one-hop communication range. On the other hand, if the range is too large, the node degree increases polynomially, causing an increase in challenge levels in communications, networking, power, and management. Therefore, physical layer designs need to jointly consider the application requirements, networking complexity, and power and management constraints so that an appropriate D2D communication range can be achieved. Furthermore, heterogeneous devices bring more complex constraints due to the varied communication capabilities and standard versions. For example, less-powerful devices may only implement a lite version of a standard with limited functionality for networking.

**Peer Discovery:** Peer discovery is a major

A user in a SSDNet ultimately has the right to determine its willingness to forward packets for others in proximity. For example, a user can set its forwarding black list and white list for the applications and other users, and it can also generally set the data rate and/or the request acceptance probability of forwarding to save energy. The flexibility in users' forwarding policies can increase the routing difficulty.

issue in SSDNet, since knowing who is around (hundreds of neighbors) quickly and efficiently is the foundation of effective communications and applications. There are two types of peer discovery methods: network assisted and ad-hoc. Network assisted solutions utilize the eNBs (evolved node B) to allocate slots within PRBs for peer discovery. LTE Direct takes a synchronized network assisted approach to discover thousands of devices in proximity (500 m). Time synchronization services and eNBs, however, may be unavailable immediately after emergencies, and the collisions may occur more frequently if UEs are mobile. Ad-hoc peer discovery solutions such as WiFi and Bluetooth are based on CSMA, which is time and energy consuming and may not work well in super dense environments. Therefore, more effort is needed to develop quick and effective D2D peer discovery methods for SSDNets.

**Opportunities and Performance Indicators:** Though the super-dense feature brings challenges mentioned above to SSDNets, the features of small-world and 5G-based time synchronization can create opportunities for designing feasible and efficient solutions. For examples, time-synchronization can make the design of congestion avoidance scheduling easier; the small-word feature limits the contention range and may bring the possibility of traffic pattern based scheduling that may reduce the difficulty caused by super-dense. The corresponding performance indicators include but are not limited to: communication range, data rate, energy consumption, maximal capacity, delays in discovery and communications, interference to other wireless communications, and discovery ratio.

## Network Layer

**Cross the Barrier of using Multi-Hop:** Multi-hop networking is the key feature of SSDNets. However, it has also been the barrier preventing the popularity of MANET applications. For examples, one may not want to relay the packets for those who are many hops away as most likely they do not have common interests; administrators do not like "multi-hop" because of the difficulty in management; and operators have no profitable model for long-distance multi-hop communications. In addition, the designs and implementations are very complex for scalable multi-hop networks, and the overheads increase at least polynomially with the increase in the number of hops. Accordingly, the idea of "small-world" can be a solution for removing the barrier as people in proximity have more chances to possess common interests, managing smaller networks is easier, making profits from the new model is positive, scalability will no longer be an issue, and deterministic optimizations can be applied for the improvements in efficiency, reliability, energy saving, delay, and throughput.

**Heterogeneous Relays:** The conventional ad-hoc routing protocols [13] are based on the assumption that all users in a network are willing to serve as relays. SSDNet changes the game first by removing this assumption. A user in a SSDNet ultimately has the right to determine its willingness to forward packets for others in proximity. For example, a user can set its forwarding black list and white list for the applications and other users, and it can also generally set the data rate and/or the request acceptance probability of forwarding to save energy. The flexibility in users' forwarding policies can increase the routing difficulty.

**No Broadcast Based Route Discovery:** The general objectives of the conventional ad-hoc routing protocols are to find/maintain acyclic routes to destinations with less energy and small communication cost. Reachability and scalability, in terms of the number of hops, are usually the concerns in design. However, the "small-world" and "super-dense" features move the focus from scalability to "node degree" as the number of hops is a small constant but the node degree is large in a SSDNet. In addition, one can see that broadcast based route discoveries, which are employed by almost all the conventional ad-hoc routing protocols, can incur large communication overheads and congestions in a super-dense environment.

**Easier and Effective Routing:** Though SSDNet brings new challenges to conventional multi-hop routing, it also presents opportunities to solve the routing problems from new angles. Under super-dense conditions, big cliques, i.e., complete subgraphs, are everywhere in a SSDNet. This means that the reachability from a source to a destination is almost guaranteed, and a large number of possible paths to reach the destination exist. In addition, under the small-world constraint, the length of a reasonable path is upper bounded by a small constant, which can significantly reduce the complexity caused by avoiding cycles. If finding a path (does not have to be an optimal one) is the primary objective, one can see that unicast-based route discoveries can have a high chance to succeed without the overheads of broadcast and exhaustive search.

**Possible Route Cache:** Moreover, we live in our own small worlds, and our activities have regular patterns and can be profiled. Therefore, "small-world" also implies regularly reappeared routing paths here and there. The lifetime of a route could be long as some users may be relatively static during a specific period. Applications may also have their traffic patterns that could be helpful to produce reappeared long life routes. As a result, the social characteristics of "small-world" provide an opportunity to map real-life routing to cyber routing so that the discovery time and the overhead of routing and route maintenance can be reduced. Furthermore, the availability of location and the employment of DTN (delay-tolerant networking) can also provide opportunities to design efficient routing protocols for SSDNets.

**Performance Indicators:** The corresponding performance indicators include but are not limited to: route discovery success ratio, route discovery delay, delivery ratio, data rate, latency, overhead, traffic balance, robustness, and stability.

## Application Layer

**Cross-Layer Design:** Conventionally, the implementations of the physical and link layers and the mechanisms of the network layer are transparent to applications. However, in SSDNets applications need to pass more information to the lower layers for more successful and efficient channel allocation, routing, and topology control in small-world and super-dense environments. For example, applications have their own priorities and traffic patterns, which can help group users into several sub-networks that operate on different channels. Within one application, users can be further grouped according to their interests (such as chat groups) and/or the conditions to successfully run the application (for instance, a much smaller node degree, such as tens, may be sufficient to guarantee the success of routing in public safety). The sub-networks derived from the groups can be less dense on their allocated channels, provide stronger privacy protection, reduce redundancy, and improve the success rate of routing as the members of the same group are more cooperative. Therefore, cross-layer designs are essential for SSDNet applications.

**Location and Energy:** Two fundamental issues that should be studied for supporting various applications are acquiring locations and saving/sharing energy. In SSDNets, infrastructures may be unavailable or untrustworthy for localization. For example, iBeacons' real locations may be different from the programmed locations after an earthquake. The location refresh rate is one second, as required by NIST for public safety. The conventional broadcast and flooding based ad-hoc localization techniques are too heavy and inappropriate for SSDNets due to the redundant communication overheads and the long delays in handling mobility. Therefore, lightly-weighted and unicast-based localization should be a direction for localization research in SSDNets. Saving energy has always been an important topic as devices may be battery-powered. In addition, energy sharing between devices should be essential as power supplies may be unavailable in emergencies.

**Extendability and Compatibility:** Due to their heterogeneous feature, SSDNet devices should have the ability to connect to and cooperate with each other, although they may run on different standard versions, which have varied functionalities and provide different levels of services. Heterogeneous applications also require backward compatibility and the potential for supporting future multi-hop applications.

## Management

**Network Monitoring:** Conventional multi-hop management in terms of network monitoring, access control, privacy protection, and trust are very challenging due to the non-centralized networking model and the large scalability in terms of the number of hops. The "small-world" feature makes it possible to deploy a small number of network monitors to cooperatively oversee the traffic in a SSDNet, though the "super-dense" feature increases the difficulty of data processing and security. As an essential component, SSDNet management plays a critical role in achieving the objective of flexible, manageable, and secure networking.

> Lightly-weighted and unicast-based localization should be a direction for localization research in SSDNets. Saving energy has always been an important topic as devices may be battery-powered. In addition, energy sharing between devices should be essential as power may be unavailable in emergencies.

**Small-World Topology Control:** In addition to routing, topology control is another important topic that has been extensively studied in MANETs [14] by considering reachability, connectivity, bandwidth, coverage, delay, network lifetime, and interference management. To meet the objectives in MANETs, wireless nodes may adjust their transmission powers, turn on/off radios, self-organize into clusters, and move to new locations. These topology control techniques have been designed for applications such as sensor networks where the whole network is considered for structured topology control (such as tree-based backbone construction). SSDNet applications are under the small-world super-dense environments, which are quite different from the conventional MANETs, and therefore have their own unique topology control objectives. For example, the topology control in SSDNets may only need to be applied to subnetworks (small-world) with more independent users who may not want to adjust transmission powers or change locations.

**Varied Topology Control:** The studies of SSDNet topology control generally need to first answer the following two questions according to the application requirements:

- Will the topology be self-centered in cyberspace or mapped from geographical regions?
- Will the topology be structured or not?

If the topology is self-centered in cyberspace, each user should have its own topology view centered at itself within the small-world radius; if the topology is mapped from geographical regions, users within the same small-world (a small geographical region) should have the same topology view. Structured topologies can be optimized for more regular (reappeared) traffic, and unstructured topologies can be more appropriate for handling mobilities and emergencies.

## Broader Discussions

**Traffic Model and Simulator:** One can see that the studies of applications' traffic models are important to guide the protocol designs in SSDNets, and that the traffic generators are essential to evaluate the protocols' performance in experiments and simulations. So far "super-dense" and the corresponding traffic models are still missing from the existing testbeds, experiments, and simulators. Therefore, efforts are needed to integrate the modules of SSDNets into the network simulators so that future application and protocol designs can be evaluated properly.

**Engineering Issues:** Besides the research challenges, SSDNets also face many engineering issues. There are still no commercialized ProSe devices and no mature smartphone based multi-hop implementations. The native smartphone operating system level support for multi-hop networking is currently very limited. A MANET android app was designed in [15], where MANET and DTN were jointly used to connect an isolated

Currently, applications with LTE Direct must work with mobile operators as they could be the spectrum holders for LTE Direct. The business models for D2D applications need more investigation to provide a better user experience and guarantee operators' profits. In addition to increasing profit, SSDNet would also improve network capacity via offloading local traffic to D2D communications.

disaster area to an unaffected area with a delay of fewer than 20 seconds. Today, hardware and software limitations are still the barriers for the successful implementations of SSDNets on mobile devices.

**Dissemination:** Operators hold the key to enable LTE Direct and people need more time to accept the concept of D2D multi-hop networking as their smartphone batteries may be used to relay others' packets. Currently, applications with LTE Direct must work with mobile operators as they could be the spectrum holders for LTE Direct. The business models for D2D applications need more investigation to provide a better user experience and guarantee operators' profits. In addition to increasing profit, SSDNet would also improve network capacity via offloading local traffic to D2D communications. It is essential to have research tailored to disseminate the SSDNet ideas and apps to people via different channels such as commercialization, training, and publications.

## Conclusion

This article proposes the concept of small-world super-dense D2D wireless networking. Research opportunities and challenges are elaborated along with broader discussions for the success of SSDNet design and implementations.

## References


[1] C. E. Perkins *et al.*, *Ad Hoc Networking*, Addison-Wesley Reading, 2001, vol. 1.

[2] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," *IEEE JSAC*, vol. 23, no. 2, 2005, pp. 201–20.

[3] T. S. Rappaport *et al.*, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol. 1, 2013, pp. 335–49.

[4] J. Liu *et al.*, "Device-to-Device Communication in LTE-Advanced Networks: A Survey," *IEEE Commun. Surveys Tutorials*, vol. 17, no. 4, fourth quarter 2015, pp. 1923–40.

[5] W. Yu *et al.*, "Ultra-Dense Networks: Survey of State of the Art and Future Directions," *Proc. 2016 25th Int'l. Conf. Computer Commun. Networks (ICCCN)*, Aug. 2016, pp. 1–10.

[6] W. Sun *et al.*, "An Analysis Framework for Interuser Interference IEEE 802.15.6 Body Sensor Networks: A Stochastic Geometry Approach," *IEEE Trans. Vehicular Technology*, vol. 65, no. 10, Oct. 2016, pp. 8567–77.

[7] I. F. Akyildiz and X. Wang, "A Survey on Wireless Mesh Networks," *IEEE Commun. Mag.*, vol. 43, no. 9, Sept. 2005, pp. S23–30.

[8] S. N. Swain, S. Mishra, and C. S. R. Murthy, "A Novel Spectrum Reuse Scheme for Interference Mitigation in a Dense Overlay D2D Network," *Proc. 2015 IEEE 26th Annual Int'l. Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Aug. 2015, pp. 1201–05.

[9] J. Liu *et al.*, "On the Outage Probability of Device-to-Device-Communication-Enabled Multichannel Cellular Networks: An RSS-Threshold-Based Perspective," *IEEE JSAC*, vol. 34, no. 1, Jan. 2016, pp. 163–75.

[10] J. Liu *et al.*, "Device-to-Device Communications Achieve Efficient Load Balancing in LTE-Advanced Networks," *IEEE Wireless Commun.*, vol. 21, no. 2, Apr. 2014, pp. 57–65.

[11] J. Liu *et al.*, "Device-to-Device Communications for Enhancing Quality of Experience in Software Defined Multi-Tier LTE-A Networks," *IEEE Network*, vol. 29, no. 4, July 2015, pp. 46–52.

[12] A. Asadi, Q. Wang, and V. Mancuso, "A Survey on Device-to-Device Communication in Cellular Networks," *IEEE Commun. Surveys Tutorials*, vol. 16, no. 4, fourth quarter 2014, pp. 1801–19.

[13] A. Boukerche *et al.*, "Routing Protocols in Ad Hoc Networks: A Survey," *Computer Networks*, vol. 55, no. 13, 2011, pp. 3032–80; available: //www.sciencedirect.com/science/article/pii/S1389128611001654.

[14] M. Li, Z. Li, and A. V. Vasilakos, "A Survey on Topology Control in Wireless Sensor Networks: Taxonomy, Comparative Study, and Open Issues," *Proc. IEEE*, vol. 101, no. 12, Dec. 2013, pp. 2538–57.

[15] H. Nishiyama, M. Ito, and N. Kato, "Relay-by-Smartphone: Realizing Multihop Device-to-Device Communications," *IEEE Commun. Mag.*, vol. 52, no. 4, Apr. 2014, pp. 56–65.


## Biographies


Wei Cheng [SM] (wcheng3@vcu.edu) is an assistant professor in the Department of Computer Science, Virginia Commonwealth University. He received his Ph.D. degree in computer science from the George Washington University, Washington DC, in 2010. He was a postdoc scholar in UC Davis from 2011 to 2012. His research interests include localization, VAENTs, fog computing, and wireless networks. His research has been continuously supported by NSF and NIST. He is a senior member of IEEE and a member of ACM.

Jiguo Yu [SM] (jiguoyu@sina.com) received his Ph.D. degree in mathematics from Shandong University in 2004. He became a full professor in the School of Computer Science, Qufu Normal University, Shandong, China in 2017. He is currently a full professor in the School of Information Science and Engineering, Qufu Normal University. His main research interests include wireless networks, distributed algorithms, peer-to-peer computing and graph theory. In particular, he is interested in designing and analyzing algorithms for many computationally difficult problems in networks. He is a senior member of IEEE, a member of ACM and a senior member of the CCF (China Computer Federation).

Feng Zhao [M] (zhaofeng@guet.edu.cn) is currently a full professor in the School of Information and Communications, Guilin University of Electronic Technology. He received his Ph.D. degree in communication and information systems from Shandong University, China, in 2007. His research interests include cognitive radio networking, MIMO wireless communications, cooperative communications, and smart antenna techniques.

Xiuzhen Cheng [F] (cheng@gwu.edu) received the M.S. and Ph.D. degrees in computer science from the University of Minnesota Twin Cities in 2000 and 2002, respectively. She is a professor in the Department of Computer Science, The George Washington University, Washington DC. Her current research interests include cyber physical systems, wireless and mobile computing, sensor networking, wireless and mobile security, and algorithm design and analysis. She worked as a program director for the US National Science Foundation (NSF) for six months in 2006 and joined the NSF again as a part-time program director in April 2008. She received the NSF CAREER Award in 2004. She is a senior member of the IEEE.