A Decade of Research in Opportunistic Networks: Challenges, Relevance, and Future Directions

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After a decade of research, opportunistic networks have not yet been ubiquitously deployed. The authors explore the reasons for their absence. They take a step back, and first question whether the use-cases that are traditionally conjured to motivate opportunistic networking research are still relevant. They also discuss emerging applications that leverage the presence of opportunistic connectivity.

Abstract

Opportunistic networks are envisioned to complement traditional infrastructure-based communication by allowing mobile devices to communicate directly with each other when in communication range instead of via the cellular network. Due to their design, opportunistic networks are considered to be an appropriate communication means in both urban scenarios where the cellular network is overloaded, as well as in scenarios where infrastructure is not available, such as in sparsely populated areas and during disasters. However, after a decade of research, opportunistic networks have not yet been ubiquitously deployed. In this article we explore the reasons for their absence. We take a step back, and first question whether the use cases that are traditionally conjured to motivate opportunistic networking research are still relevant. We also discuss emerging applications that leverage the presence of opportunistic connectivity. Further, we look at past and current technical issues, and we investigate how upcoming technologies would influence the opportunistic networking paradigm. Finally, we outline some future directions for researchers in the field of opportunistic networking.

Introduction

In recent years we have witnessed the spectacular success of the mobile Internet, driven by the rise of smart mobile devices. The demand for data is exponentially increasing as more and more services are based on a cloud infrastructure with a prediction of 24 EB of monthly mobile data traffic by 2019 according to Cisco's Visual Networking Index. At this pace, the mobile Internet is about to become a victim of its own success. On one hand, improving the infrastructure is becoming increasingly costly, and coping with the demand during large gatherings such as sports events is already hardly feasible. Furthermore, in some places, even when communication is technically possible, it might be restricted by censorship, thus blocking information dissemination. On the other hand, in sparsely populated areas the deployment of communication infrastructure might not be economically beneficial for operators. Finally, infrastructure may break during natural or man-made disasters, leaving rescue services and people in need unable to communicate.

Opportunistic networks, or *OppNets* (sometimes referred to as pocket-switched networks [1] and people-centric networks [2]), are a special type of mobile ad hoc networks (MANETs) in which human-carried mobile devices (often referred to as nodes) communicate directly via some short-range wireless technology such as Wi-Fi or Bluetooth whenever they are in transmission range. By design, OppNets are infrastructure-free: nodes *store* data, and *carry* it according to the underlying user mobility until a new communication opportunity arises to *forward* the data. This store-carry-forward paradigm was first introduced in the general field of delay-tolerant networking (DTN) [3]. While DTN embraced the idea of leveraging mobility as a means of transporting information, it still kept the traditional Internet-inspired user-centric approach for delivering data between particular source-destination pairs. To facilitate data dissemination, various routing algorithms were introduced [4]. Contrary to DTNs, in OppNets the focus shifts from user-centric to *content-centric* data dissemination. This reduces network complexity, as choosing appropriate intermediate nodes for forwarding information is no longer a priority. Instead, data dissemination depends on the mobility patterns of humans as well as some shared content interests. Due to these characteristics, OppNets have been considered as a potential solution to complement the infrastructure and mitigate the aforementioned shortcomings that network operators are experiencing. However, after a decade of research efforts, OppNets have not yet been widely deployed. It may thus be time to take a step back and pose the question: *Why are OppNets not used to solve these problems?*

There are two main reasons OppNets have never been deployed beyond small-scale testbeds. First, OppNets did not present companies with a clear business case. Instead, the infrastructure-free design has been perceived as a threat by mobile operators. Second, even if a particular business case were available, the prohibitive battery consumption of the mobile devices to maintain the network would still prevent the deployment of OppNets. To discover communication opportunities without the aid of an infrastructure, the mobile devices need to continuously advertise their presence in the network. With the available technologies, this operation is too power-hungry

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for the limited battery capacity of modern smartphones [5].

In this article we look beyond the current showstoppers and first ask ourselves the question: *Is opportunistic communication still a relevant concept in today's highly connected world?* We revisit well established use cases, and discuss their applicability and positioning with respect to other upcoming technologies. Then we take a look into the future, examining what emerging applications and technologies are on the horizon and how they might impact the paradigm of opportunistic communication. Finally, we outline the next steps that could lead to eventual deployment of OppNets.

Are OppNets Still Relevant?

In this section we evaluate the relevance of the motivational scenarios used to justify research in the field of opportunistic networks during the past decade, and examine how well suited OppNets currently are for these scenarios in comparison to newly emerging technologies.

Classical Use Cases

For a decade researchers have been searching for the "killer application" that will boost the global deployment of OppNets. Below are four distinct application areas that have been promoted in the community.

Cellular Network Offloading: Operators struggle to cope with the traffic demands of large crowds, especially if they are sporadic in nature, such as festivals and street fairs. They deploy ever smaller cells and greatly overprovision the supply, but this is costly and is still unable to deal with unforeseen traffic peaks. Mobile operators could utilize OppNets to offload their infrastructure by seeding popular content to a few devices in a crowded space which then opportunistically disseminate it to others in their vicinity.

However, as operators do not like to relinquish control and as users still expect to have their requests for data answered with minimal delay, the type of OppNets that could succeed in this scenario might be operator controlled.

Communication in Challenged Areas: A challenged area is often defined as an area in which infrastructure is partially or fully unavailable. Reasons for such unavailability may be due to:

1. A natural or man-made disaster that has destroyed available infrastructure
2. A lack of economic motivation for deploying infrastructure, for instance, in sparsely inhabited regions
3. The inaccessibility of certain areas, for instance, in mines

Due to their infrastructure-free design, OppNets enable local communication, and could even serve as a bridge between the challenged areas and the infrastructure (wherever available). During disasters, this could be of great importance for supporting the operation of rescue teams. In sparsely populated areas, both above or underground (e.g., in mines), OppNets could provide an alternative means of communication.

Censorship Circumvention: OppNets may become an appropriate tool for enabling freedom of speech in regions governed by oppressive institutions that are inclined to censor traditional communication via the Internet. Participants in opportunistic communication benefit from the fact that links established in an opportunistic manner are hard to intercept or jam, and individual users are not easy to track down, especially in crowded scenarios. However, simply promoting OppNets as a censorship circumvention technology may not appeal to governmental bodies. Therefore, this application might only be seen as an added value instead of a primary solution.

Proximity-Based Applications: A promising use case for OppNets are proximity-based applications. Proximity-based applications take advantage of the co-location of nodes to provide add-on services on top of available infrastructure.

However, employing OppNets in the proximity-based applications domain for providing services such as proximal social networking has failed due to the following two limitations:

1. The lack of an explicit business model
2. The possibility to provide similar functionality via traditional centralized communication

A special use case of proximity-based applications for OppNets might be seen in applications that target people in the creative sector (e.g., artists or musicians); applications have been tailor-made for these industries and have been met with interest.

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New Research Directions

In addition to the classical use cases, in recent years the research community has been investigating other promising application areas that exploit the characteristics of opportunistic communication.

Opportunistic Mobile Sensing: Today's mobile devices (both smartphones and wearables) are equipped with a rich set of embedded sensors including accelerometers, cameras, microphones, GPS, and more. Opportunistic mobile sensing exploits all of these sensing devices available in an environment to collect data in a fully automated way [6]. It is expected that larger populations may engage in the data collection process. The objective of opportunistic mobile sensing is to investigate human behaviors and socio-economic relationships by analyzing the digital footprint of people in the surrounding physical world.

Opportunistic Mobile Computing: OppNets make use of contact opportunities among mobile devices purely in the context of data dissemination. However, when two (or more) devices are in direct communication range, they could potentially share more than just data; for example, they could exploit each other's software and hardware resources, and even execute tasks remotely. This lays the foundation for the newly emerging concept of opportunistic computing [7]. The objective of opportunistic computing is to enrich the functionality of a single device by allowing nodes to utilize resources on other devices in proximity in a trustable and secure way. Opportunistic computing is expected to find application in pervasive healthcare, intelligent transportation systems, and crisis management, among other fields.

However, as these use cases are not directly targeted at providing connectivity, their direct competition is the same or a similar service provided over a centralized communication infrastructure. If these use cases perform better when using opportunistic communication, most proba-

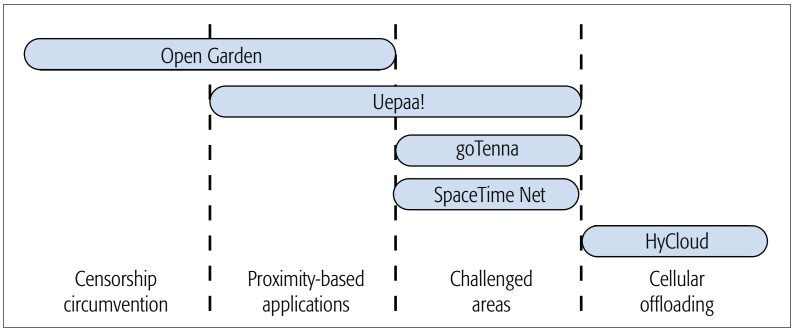

Figure 1. Distribution of companies utilizing the opportunistic networking paradigm across potential use case scenarios. It is interesting to notice that most solutions cater to providing connectivity in challenged areas. Data offloading, which may be the most economically beneficial application, has not yet seen actual industrial deployments, only early-stage prototyping.

bly stemming from reasons linked to the classical use case of data offloading, such novel services can indeed be seen as an additional motivator.

Alternative Solutions for Future Connectivity

OppNets are not the only suggested paradigm for overcoming the limitations in connectivity listed above. In 2014, four companies publicly announced their goal of providing or facilitating mobile connectivity and Internet access on a global scale. We can divide them into two broad categories based on the way they mitigate infrastructure: floating and orbital.

The two main representatives of floating infrastructure are Google's Project Loon and Internet.org by Facebook. Project Loon aims to provide air-floating cellular infrastructure in the form of LTE-equipped balloons. Initial trials show that the balloons can be kept in the air for months, and public trials began in 2016. In contrast, the Internet.org initiative intends to use solar-powered drones to provide a backbone to scattered cellular base stations that provide connectivity in remote areas.

Orbital infrastructure is suggested by SpaceX and OneWeb, which intend to provide connectivity through a swarm of satellites in low Earth orbit. In contrast to current geostationary satellite technologies, supporting an infrastructure of satellites at lower orbits would offer users shorter end-to-end communication delays, but at a cost of a larger amount of equipment. Expected initial trials are scheduled for 2020.

OppNets vs. Future Connectivity Solutions

In 2009 researchers in the field of OppNets and DTN stated that "delay-tolerant systems will progress to become the mainstream default networking paradigm" [8]. Nowadays however, with emerging paradigms for providing global connectivity such as floating and orbital infrastructures, a valid question is whether some of the classical OppNet use cases could be better addressed by these infrastructures instead. Table 1 summarizes the applicability of different approaches to the scenarios introduced earlier.

As expected, the emerging paradigms are best suited for the scenarios for which they were initially designed, that is, providing connectivity in challenged areas, such as sparsely inhabited areas as well as during disasters. Floating infrastructures, especially Project Loon, are perfectly suited to provide Internet access to underdeveloped regions. Depending on the speed with which the network can be rearranged, communication might be provided during or after disasters. In contrast, orbital infrastructure is likely to be always present, and thus immediately available during disasters. Enabling communication via a satellite is also well suited for underdeveloped regions, but the cost of putting infrastructure in the orbit might make the solution expensive.

However, both floating and orbital infrastructures are not appropriate when targeting communication in inaccessible areas, as in the case of providing connectivity in mines. Furthermore, due to the larger cell sizes, they are ill suited for supporting proximity-based services. Offloading mobile data is also not a potential application since floating and orbital infrastructures are facing the same issues with traffic volumes as current terrestrial deployments of base stations. Finally, in the case of censorship circumvention, access to these emerging technologies may be blocked by oppressive governmental bodies as is done with current infrastructure.

We can thus conclude that the concept of OppNets is relevant to this day. While some of the classical use case scenarios, such as communication in sparsely populated areas, may be better served by emerging communication paradigms, there is still a strong case for the usage of opportunistic communication, most notably in the context of mobile data offloading and proximity-based applications. The latter is further strengthened by the increasing interest in the Internet of Things (IoT) domain where direct communication between devices is dominant. In fact, as of Release 12, the Third Generation Partnership Project (3GPP) is focusing on utilizing device-to-device communications for providing proximity-based services on top of current cellular infrastructure [9], which is an indication of the potential deployment of OppNets. Finally, the emerging application paradigms that make use of opportunistic communication, such as opportunistic mobile sensing and opportunistic mobile computing, can be construed as a positive sign for the future development of OppNets.

OppNets Today

The Research View — Most research on OppNets addresses issues in the area of content dissemination, with the focus being on routing and mobility modeling as enablers of data sharing. Due to the absence of centralized control, security and privacy have also been investigated. The high battery consumption of nodes in OppNets has led to designing energy-efficient discovery protocols. However, not all research topics are fully exhausted, as we show later.

The Industry View — Few industrial applications have been developed on top of the opportunistic networking paradigm, as shown in Fig. 1. *Spacetime networks* base their business model on an opportunistic router developed in the SCAMPI [10] research project and aim to deploy OppNets as a communication tool in challenged environments such as mines and underground tunnels. *Uepaa!* has developed an alpine safety application to be used in areas with no cellular coverage.

Open Garden offered FireChat, an off-the-grid application that gained popularity during the Hong Kong protests. Both Uepaa! and Open Garden aim to release their platform with an open application programming interface (API) for the convenience of third-party developers. To circumvent the prohibitive energy costs of establishing OppNets, *goTenna* takes an entirely different approach to providing ad hoc communication capabilities. They provide an add-on device linked to the smartphone, with communication ranges of 500 m in urban areas for an operational duration of over 30 hours.

It is interesting that although mobile data offloading would be the most economically beneficial application, currently there are no real industrial applications developed. HyCloud [11] is the only academic project to prototype opportunistic networking for data offloading.

Evolution of OppNet Technology

While few companies attempt to create business models on top of the opportunistic networking concept, they all face similar technical limitations. The functional support for opportunistic communication provided by the mobile operating system is currently nonexistent. Furthermore, the lack of radio technology tailored to providing efficient device discovery at low energy cost still presents a challenge.

Brief Historic Overview

At the dawn of opportunistic networks, researchers only had access to two widely deployed technologies: Wi-Fi in ad hoc mode and Bluetooth. Wi-Fi in ad hoc mode was often the preferred radio technology for early-stage proof-of-concept implementations due to its higher data rates, longer communication ranges, and lack of manual pairing. However, researchers quickly encountered a number of limitations. First, Wi-Fi in ad hoc mode is extremely energy-hungry due to the fact that the energy spent in idle state (while trying to catch a signal) is on the same order of magnitude as that spent on actual transmission and reception of data. Due to the implicit requirement of continuous device discovery, a device can only operate for a few hours before it completely drains its battery [12]. Moreover, support for Wi-Fi in ad hoc mode is also restricted, requiring users to operate their devices in privileged mode if they are to participate in any opportunistic content sharing. This has naturally limited users' interest in OppNets.

To combat the aforementioned issues, the research community created WLAN-Opp [13], an 802.11-based technology that leverages the tethering mode of devices. However, due to the lack of standardization, WLAN-Opp has not been widely adopted in current devices, and its usage is limited solely to research activities.

Both Bluetooth and Wi-Fi have evolved since; however, neither of these technologies has become more suitable for opportunistic communication. Bluetooth Low Energy (BLE) was the first technology on the market to tackle the problem of energy-efficient device discovery. However, the required manual pairing makes it inappropriate for opportunistic networking. Furthermore, scanning intervals are on the order of minutes, which makes discovery slow, with a potential of skipping a lot of contact opportunities in dynamically changing environments such as urban areas. When Wi-Fi Direct gained momentum in 2012, it brought a new wave of excitement to the research community. However, Wi-Fi Direct was originally created as a competitor of BLE, and as such it is ill suited for performing opportunistic device discovery and communication: not only are its energy consumption profiles unbalanced, but discovery is time consuming and requires manual pairing.

Use-case scenario	OppNets	Floating infrastructure	Orbital infrastructure
Network data offloading	★★★	★★	★
Proximity-based apps	★★★	–	–
Censorship circumvention	★★★	★	★★
Inaccessible areas	★★	★	★
Disaster scenarios	★★	★★	★★★
Sparsely populated areas	★	★★★	★★★

Table 1. Comparison: OppNets vs. future connectivity paradigms. One star denotes that a paradigm is ill suited; three stars denote a good fit.

Future Technologies

The 3GPP is currently discussing the introduction of device-to-device communication as a complement to traditional communication via the cellular infrastructure. As a result, two new technologies have been proposed to allow energy-efficient proximity-based service discovery and communication for users on the go, catering to the whole potential of OppNets: unlicensed spectrum Wi-Fi Aware and in-band LTE-Direct. While there are no products available yet using these new technologies, LTE-Direct has already been implemented and tested, making it currently the only radio technology designed *specifically* for opportunistic device discovery. Due to its synchronous duty-cycling scheme, it is expected to significantly reduce the energy consumption in devices.

The fact that technologies are developed entirely for the specifics of opportunistic device discovery is partially linked to the rise of the IoT, and can be seen as a strong indication of the uprise of OppNets. It is still unclear whether OppNets would operate in unlicensed spectrum as envisioned by researchers a decade ago, whether they would be entirely under the control of cellular network operators, or if a hybrid approach would prevail. However, once a stable technological foundation is built, one that decreases the energy consumption in the devices while simultaneously allowing them to discover nodes in a quick and efficient manner, it would be technically possible for OppNets to see mass deployment.

Future Directions in OppNet Research

As the concept of OppNets remains relevant and more timely than ever, as the industry expresses interest in its potential, and as promising technological enablers are emerging on the horizon, the natural question for researchers to ask is: *What is to be done next?* In this section we first outline a three-step action plan for future research toward

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ubiquitous deployment of OppNets, and then discuss open research questions.

Action Plan toward Deployment of OppNets

First Large-Scale Experiments: While waiting for the technological progress to happen, researchers should take an active role in setting up large-scale experiments. This can be done in three possible ways:

1. By using the most energy-efficient method to establish OppNets, and recruiting people to participate in support of research with the explicit warning that energy consumption may be higher
2. By using a controlled testbed of mobile devices with a rooted or modified OS that integrates OppNet functionality in an energy-efficient way, maybe even using prototypes of future protocols such as Wi-Fi Aware
3. By using external devices such as goTenna[1] for performing long-distance experiments

Each approach has its own advantages and limitations. Implementation on smartphones provides a few options in terms of radio technology used (either Bluetooth or WLAN-Opp; using a pure ad hoc mode may also be possible if paired with additional energy saving schemes [14]). The benefit of integration in the OS is better control of duty cycling and background operation without interfering with the user. If researchers decide to use external devices such as goTenna, energy consumption on the mobile device during neighbor discovery would only depend on the energy spent on communicating with the goTenna. However, it is unclear how traffic will impact battery consumption, especially if data is also relayed for other devices.

Exploring Scalability: Large-scale deployments will result in exploring a feature of OppNets that has not previously been addressed, that is, their scalability. It is thus important to perform extensive scalability tests and determine the bounds, in terms of density of participants, below which the performance of OppNets is acceptable, also taking into account application requirements. A good way to measure scalability would be to provide OppNets as an alternative communication means during large gatherings such as outdoor festivals.

Another aspect of scalability researchers should consider is related to the abundance of services competing to use the communication opportunities. Current research efforts have only evaluated the performance under the assumption of a single available service in the opportunistic domain. Thus, it is unclear how many services would comprise a bottleneck, as well as in which scenarios this may be an actual performance issue.

Economical Validation: Finally, researchers should address the economic benefits of ubiquitous deployment of OppNets. In this context, economic validation should be understood in a broader sense than simply monetizing the OppNet concept. Instead, it should evaluate the potential benefits of OppNet deployment for all involved market players. Emerging use cases should also be considered: offloading network traffic and providing proximity-based services are a good starting point, but as deployments advance, other use cases, especially in the IoT domain, are worth investigating.

Open Research Questions

Not all research questions have been fully addressed in the domain of opportunistic communication. A number of issues still need the attention of the research community to make OppNets a reliable and trustworthy communication paradigm.

Privacy vs. Security: It is crucial to provide good privacy and security in OppNets, not only for the classical use cases but also when considering emerging application paradigms such as mobile sensing and opportunistic computing.

Currently, all proposed privacy-enabling schemes are based on changeable identifiers, to change the medium access control (MAC) address to be changed, which limits the applicability of these approaches. Furthermore, current privacy schemes are difficult to implement alongside certain security and routing schemes that make use of social information [15]. It is still not clear whether it is possible to combine privacy and security in a single scheme that satisfies all requirements. If not, the trade-off between these aspects should be thoroughly evaluated, possibly with respect to the application at hand. For example, privacy and security may be handled by the cellular infrastructure in the case of network offloading, while ensuring privacy should be a priority of the OppNet itself in the case of providing freedom of speech.

Short-Range vs. Long-Range Communication: Until now, researchers have always assumed that opportunistic communication would occur over short-range radios and be characterized by short contact durations. Thus, a general goal when designing protocols for neighbor discovery has been to provide quick and efficient discovery mechanisms. However, with the advances of 3GPP's LTE-Direct as well as emerging products like goTenna, which promise to operate at ranges of up to 500 m in urban environments, it may be necessary to re-evaluate the assumptions for opportunistic communication, and investigate the implication of long-range communication links on both protocol design and performance. It is possible that long-range communication links are better suited for implementing the well studied MANET paradigm where mobility of nodes is obscured instead of explicitly utilized. A longer range might, however, increase interference and thus result in lower capacity for a covered area (less spectral reuse).

Concluding Remarks

After a decade of research in the field of opportunistic networking, are we about to witness the age of OppNets? The research area is mature, as most research questions have been addressed. However, implementations have been scarce, thus making large-scale evaluations impossible. As of now, only a few start-up companies have ventured into creating products based on the opportunistic networking paradigm.

Meanwhile, 3GPP coined the term *device-to-device* (D2D) communication to define a concept similar to opportunistic networking. In D2D,

[1] www.gotenna.com

devices are allowed to establish a direct communication link and exchange information when in range, but under the supervision of the network operator. In other words, the cellular network partially or fully assists with one or more procedures during the connection establishment phase, such as authentication and radio resource allocation. Although OppNets are designed to be entirely infrastructure-free, the fundamental principles of opportunistic networking are really not dependent on the involvement of the cellular network in the connection establishment process. Thus, it may be valuable for researchers in the OppNet community to transfer the knowledge they have cultivated over the past decade toward the D2D domain.

Although employing OppNets is advantageous in scenarios where the network is unavailable or inaccessible (Table 1), opportunistic communication is best suited for providing proximal services such as data offloading, proximal social networking and proximal entertainment. However, such applications would require cellular operators to relinquish some of the network control. On the contrary, network-assisted D2D as defined by 3GPP allows operators to preserve their control over the network. However, it raises privacy concerns as communicating devices are expected to reveal their identity as well as periodically report their location. Thus, it is still an open question how D2D and OppNets will coexist as proximity-based networks of the future.

References

[1] P. Hui *et al.*, "Pocket Switched Networks and Human Mobility in Conference Environments," *Proc. ACM WDTN*, 2005, pp. 244–51.

[2] M. Conti *et al.*, "From MANET to People-Centric Networking: Milestones and Open Research Challenges," *Computer Commun.*, vol. 71, 2015, pp. 1–21.

[3] K. Fall, "A Delay-Tolerant Network Architecture for Challenged Internets," *Proc. ACM SIGCOMM*, 2003, pp. 27–34.

[4] S. Basagni *et al.*, Eds., *Mobile Ad Hoc Networking: The Cutting Edge Directions*, 2nd ed., Wiley-IEEE Press, 2013.

[5] S. Trifunovic *et al.*, "Adaptive Role Switching for Fair and Efficient Battery Usage in Device-to-Device Communication," *ACM SIGMOBILE Mobile Computing and Commun. Rev.*, vol. 18, no. 1, 2014, pp. 25–36.

[6] N. Lane *et al.*, "A Survey of Mobile Phone Sensing," *IEEE Commun. Mag.*, vol. 48, no. 9, Sept. 2010, pp. 140–50.

[7] M. Conti *et al.*, "From Opportunistic Networks to Opportunistic Computing," *IEEE Commun. Mag.*, vol. 48, no. 9, Sept. 2010, pp. 126–39.

[8] A. Lindgren and P. Hui, "The Quest for a Killer App for Opportunistic and Delay Tolerant Networks," invited paper, *Proc. ACM CHANTS*, 2009, pp. 59–66.

[9] 3GPP Tech. Spec. Group Services and System Aspects, "Feasibility study for Proximity Services (ProSe)," Release 12, TR 22.803 v. 12.2.0, June 2013.

[10] M. Pitkänen *et al.*, "Scampi: Service Platform for Social Aware Mobile and Pervasive Computing," *SIGCOMM Comp. Commun. Rev.*, vol. 42, Sept. 2012, pp. 503–08.

[11] J. Danihelka, D. Giustiniano, and T. Hossmann, "Hycloud: A System for Device-to-Device Content Distribution Controlled by the Cloud," *Proc. IEEE WoWMoM*, June 2014, pp. 1–5.

[12] Ó. Helgason *et al.*, "A Mobile Peer-to-Peer System for Opportunistic Content-Centric Networking," *Proc. ACM SIGCOMM MobiHeld Wksp.*, 2010.

[13] S. Trifunovic *et al.*, "Wlan-Opp: Ad-Hoc-Less Opportunistic Networking on Smartphones," *Ad Hoc Networks*, vol. 25, Part B, no. 0, 2015, pp. 346–58.

[14] S. T. Kouyoumdjieva and G. Karlsson, "Energy-Aware Opportunistic Mobile Data Offloading for Users in Urban Environments," *Proc. IFIP/TC6 Networking*, 2015.

[15] M. Li *et al.*, "Swing & Swap: User-Centric Approaches towards Maximizing Location Privacy," *Proc. WPES*, ACM, 2006, pp. 19–28.

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