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SPECIAL SECTION ON 5G WIRELESS TECHNOLOGIES: PERSPECTIVES OF THE NEXT GENERATION MOBILE COMMUNICATIONS AND NETWORKING

Device-to-Device Communications for National Security and Public Safety

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ABSTRACT Device-to-device (D2D) communications have been proposed as an underlay to long-term evolution (LTE) networks as a means of harvesting the proximity, reuse, and hop gains. However, D2D communications can also serve as a technology component for providing public protection and disaster relief (PPDR) and national security and public safety (NSPS) services. In the United States, for example, spectrum has been reserved in the 700-MHz band for an LTE-based public safety network. The key requirement for the evolving broadband PPDR and NSPS services capable systems is to provide access to cellular services when the infrastructure is available and to efficiently support local services even if a subset or all of the network nodes become dysfunctional due to public disaster or emergency situations. This paper reviews some of the key requirements, technology challenges, and solution approaches that must be in place in order to enable LTE networks and, in particular, D2D communications, to meet PPDR and NSPS-related requirements. In particular, we propose a clustering-procedure-based approach to the design of a system that integrates cellular and *ad hoc* operation modes depending on the availability of infrastructure nodes. System simulations demonstrate the viability of the proposed design. The proposed scheme is currently considered as a technology component of the evolving 5G concept developed by the European 5G research project METIS.

INDEX TERMS Wireless communications, cellular networks, ad hoc networks, mobile communications.

I. INTRODUCTION

Early work on device-to-device (D2D) communications focused on so-called commercial or general use cases, in which some contents or real-time information needs to be exchanged between parties in close proximity to one another [1], [2]. In particular, in the so-called *overlaid* mode, D2D communications operate in licensed spectrum, but remain completely transparent to the cellular (primary) users [1]. In contrast, when the D2D layer operates as an *underlay*, the cellular base station controls the operation of D2D users by maintaining a control plane association [2]. The advantages of D2D communications compared with the traditional cellular method (via a cellular base station) include the proximity, reuse, and hop gains that ultimately improve the spectral and energy efficiency of the system [3] when D2D communications take place in the cellular spectrum.

Along another line, several papers have proposed the integration of short-range communications and adhoc networking in cellular networks; see [4]–[6] and the references therein. It has been found that short-range communication can take advantage of a cellular control layer in spreading of content in a peer-to-peer fashion between mobile users relying on unlicensed spectrum resources [4]. Furthermore, ad-hoc relaying stations can not only increase the system capacity, but also reduce the transmission power for mobile hosts and extend the system coverage [5]. Finally, spectrum-sharing schemes designed to make better use of licensed spectrum by allowing D2D users to opportunistically transmit while keeping the interference level within a tolerated interference temperature can achieve significant power savings [6].

A common aspect of cellular-assisted and -controlled short-range communications technologies, including the underlay, overlay, or unlicensed spectrum based approaches, is that they rely on the availability and involvement of the cellular infrastructure. By themselves, these technologies do not provide a means for a graceful degradation of connectivity

or content access services in case the cellular infrastructure becomes partially or completely damaged or dysfunctional. Ideally, short-range or local communication should be maintained in the absence of infrastructure nodes, but should be able to take advantage of cellular functionality when parts of or the whole infrastructure remains intact.

Recently, there has been a growing interest in applying commercial cellular technologies to public safety applications. In the USA, for example, the National Public Safety Telecommunications Council and other organizations have expressed interest in defining an interoperable national standard for the next-generation national security and public safety (NSPS) network with broadband capabilities. The USA has reserved spectrum in the 700 MHz band for an LTE-based public safety network and in early 2012 committed US$7 billion to funding [7]. Similarly, European agencies are working together in the Electronic Communications Committee of the the European Conference of Postal and Telecommunications Administrations to establish a harmonized frequency band for public safety broadband services and to evaluate the spectrum needs for a public protection and disaster relief (PPDR) communication system.

Recognizing the importance of the public safety community and the need for NSPS and PPDR type of broadband services and the opportunity to establish common technical standards for commercial cellular and public safety, the 3rd Generation Partnership Project (3GPP) has started to study the scenarios, requirements, and technology enablers related to NSPS and PPDR. In the context of 5G wireless networks, the METIS project develops D2D technology components applicable in emergency situations [14]. Not surprisingly, direct D2D communication is expected to be a key component of this project. However, in contrast to fully network-assisted schemes, it is also necessary to develop solutions for situations with no or partial network coverage.

In this paper, we review some of the NSPS scenarios and key requirements and discuss solutions to such requirements. We propose a clustering scheme that builds on and extends the network-assisted underlay D2D technology and is able to dynamically adjust its operation depending on the availability of infrastructure nodes and thereby meet the requirements of disaster and emergency situations.

The next section summarizes the NSPS scenarios and discusses some of the key requirements. Next, Section III proposes a solution approach that builds on the network assisted D2D communication technique and extends it by the concept of clustering. Section IV discusses the protocol structure of the hybrid cellular-cluster and D2D based system, while Section V discusses the performance aspects. Section VI concludes the paper.

II. NATIONAL SECURITY AND PUBLIC SAFETY SCENARIOS AND REQUIREMENTS

Communication for NSPS and PPDR poses a number of specific requirements not always found in traditional cellular communication. One of the key requirements is robustness

and ability to communicate irrespective of the presence or absence of a fixed infrastructure. In many cases there is cellular coverage in the area which can be exploited for communication. However, there are scenarios in which this is not possible, for example in long tunnels, inside some buildings, or in situations when the infrastructure has collapsed due to an earthquake [7]. Although some of these scenarios can be addressed by temporary truck-mounted base stations (BS) moved into the disaster area, support for direct D2D communication remains a crucial requirement for NSPS systems [8]. Direct D2D communication can also be used for relaying where a terminal enjoying network coverage relays communication to/from a terminal outside the coverage area (see the examples in Figure 1) or to boost capacity in case the cellular network is congested.

Group communication, including push-to-talk type of communication, is another example of a requirement typically not supported in traditional cellular systems but highly desirable, for example when a dispatcher needs to address multiple officers working in an emergency situation (lower left corner of Figure 1). Similarly, the need for differentiated access levels is more pronounced in an NSPS scenario than in its cellular counterpart. Although cellular systems may have mechanisms to prioritize emergency calls over 'regular' calls, NSPS typically needs multiple priority levels to ensure prioritization of mission-critical communication.

While spectral efficiency may not be a critical requirement in emergency situations, energy efficiency and extended battery lifetime is often crucial. Time synchronization between terminals, implying that efficient discontinuous reception can be implemented, is therefore considered beneficial for both device discovery and D2D communications [12].

Traditionally, NSPS-specific communication systems such as *Terrestrial Trunked Radio* (TETRA) and *Project 25* (P25) are used to support NSPS. Although many of the NSPS requirements are fulfilled by such systems, the data rates provided are modest, a few hundred kbit/s at most, and they cannot provide satisfactory support of NSPS scenarios [9] requiring data rates on par with modern mobile broadband systems such as LTE [7]. Furthermore, relying on a separate system for NSPS implies that a responding officer may need to carry multiple devices – an NSPS device for mission-critical communication as well as an LTE terminal for high data rate services. In addition, NSPS terminals cannot enjoy the economy-of-scale associated with commercial LTE terminals. Hence, there is a great interest in, to the extent possible, relying on commercial technologies such as LTE also for NSPS applications.

In particular, the 3GPP, as part of the work on LTE Releases 12 and 13, is working on enhancements in the areas of:

- Proximity services, enabling direct D2D communication between terminals in the close proximity of each other;
- Group communication, including one-to-many communication.

A key aspect in the design is the dynamic transitions between network-supported and the so-called *stand-alone*
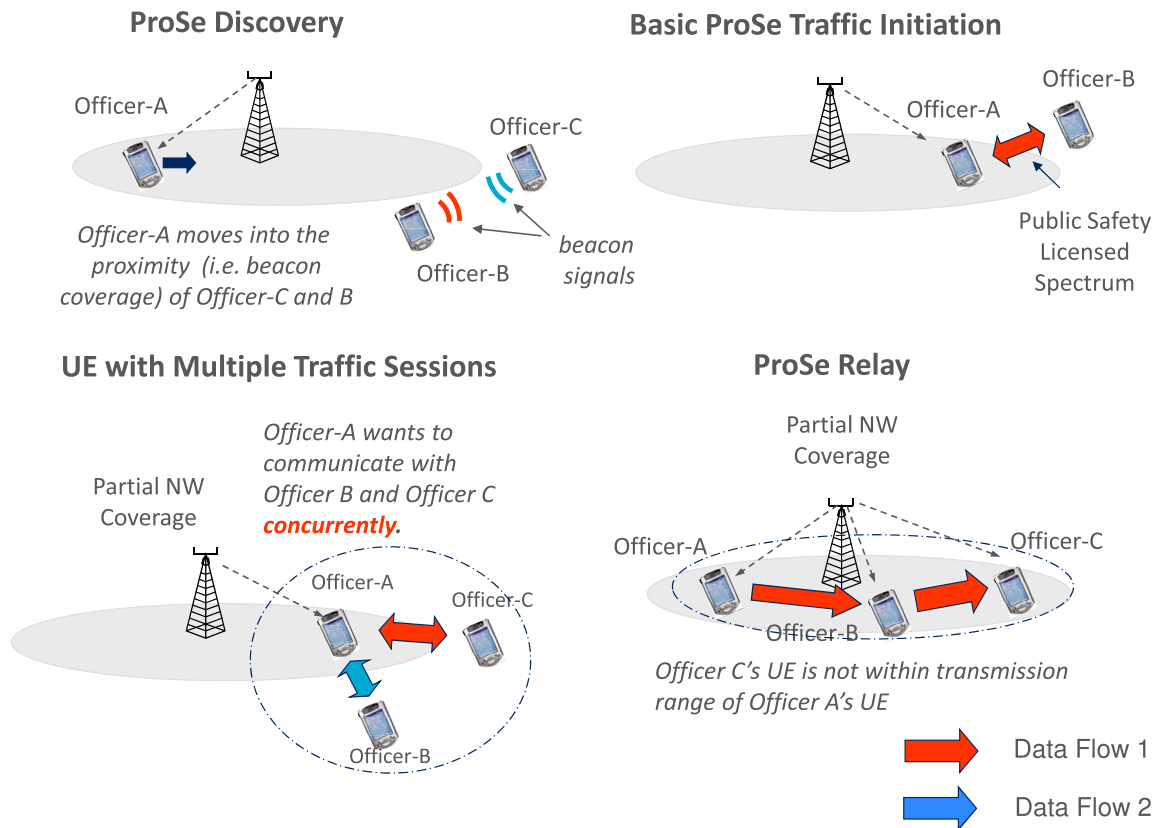
ProSe Discovery

Officer-A

Officer-C

Officer-A moves into the proximity (i.e. beacon coverage) of Officer-C and B

Officer-B

beacon signals

Basic ProSe Traffic Initiation

Officer-B

Officer-A

Public Safety Licensed Spectrum

UE with Multiple Traffic Sessions

Partial NW Coverage

Officer-A wants to communicate with Officer B and Officer C ***concurrently****.*

Officer-A

Officer-C

Officer-B

ProSe Relay

Partial NW Coverage

Officer-A

Officer-C

Officer-B

Officer C's UE is not within transmission range of Officer A's UE

Data Flow 1

Data Flow 2

FIGURE 1. Examples of NSPS and PPDR scenarios in which rescue personnel, including officers with public safety UEs, must be able to communicate in situations in which the cellular BS may provide only partial network coverage. According to TR 22.803 [8], such scenarios include ProSe Discovery, Basic ProSe Traffic Initiation, UE with Multiple Traffic Sessions and ProSe Relay.

D2D communication (Figure 2). Stand-alone D2D communication refers to the case when network coverage is not available or the BS cannot establish a control association with the devices under its coverage area due to malfunctioning [8].

To this end, the 3GPP is currently considering the requirements and roles of public safety user equipments (PS UEs) in various NSPS scenarios, including those depicted in Figure 1. Such PS UEs may have special capabilities in terms of transmit power levels, radio resource control and synchronization as will be discussed later. Stand-alone operation is clearly required for situations without network coverage, but in situations in which there is (partial) network coverage, the network can provide assistance in order to increase the overall performance. The network can, for example, provide time synchronization, assist with radio resource management, and support ciphering and authentication. In the absence of network coverage, these functions need to be provided by the terminals themselves, which typically leads to less efficient operation.

III. SOLUTION APPROACH BASED ON CLUSTERING AND D2D COMMUNICATIONS
A. THE CONCEPT OF CLUSTERING
To benefit from network-controlled D2D communication [2], [3], we propose that the NSPS solution be based on network-assisted underlay D2D communication solutions

in such a way that, in the absence of network coverage, PS UEs take over some of the functionality of the network. When network coverage is partially available, PS UEs can be smoothly integrated in the infrastructure; in the absence of infrastructure nodes, however, PS UEs provide the network assistance required by the underlaid devices.

The key architecture element of the proposed concept is the *cluster*, which consists of a cluster head (CH) node that provides key functions of a cellular base station and the attached devices. To facilitate a smooth integration of clusters and cells (where available) and to take advantage of and extend the concept of underlaid D2D communications, the following UE roles are introduced:

- *Cluster Head (CH):* At any point in time, there is exactly one CH implemented by a PS UE within a cluster. The CH has the roles of distributing synchronization signals within its cluster, owning the radio resources, acting as a gateway between the cluster and neighboring clusters (it may implement, for example, higher (Internet Protocol, IP) layer routing), and controlling the UEs within its cluster. Such controlling functionality helps to manage radio resources in, for example, scenarios like the *UE with Multiple Traffic Sessions* in Figure 1.

- *Synchronization Source (SS):* The task of the SS is to provide the CH with a synchronization reference, which is essential for the CH node to be able to act as CH and to smoothly integrate clusters in the
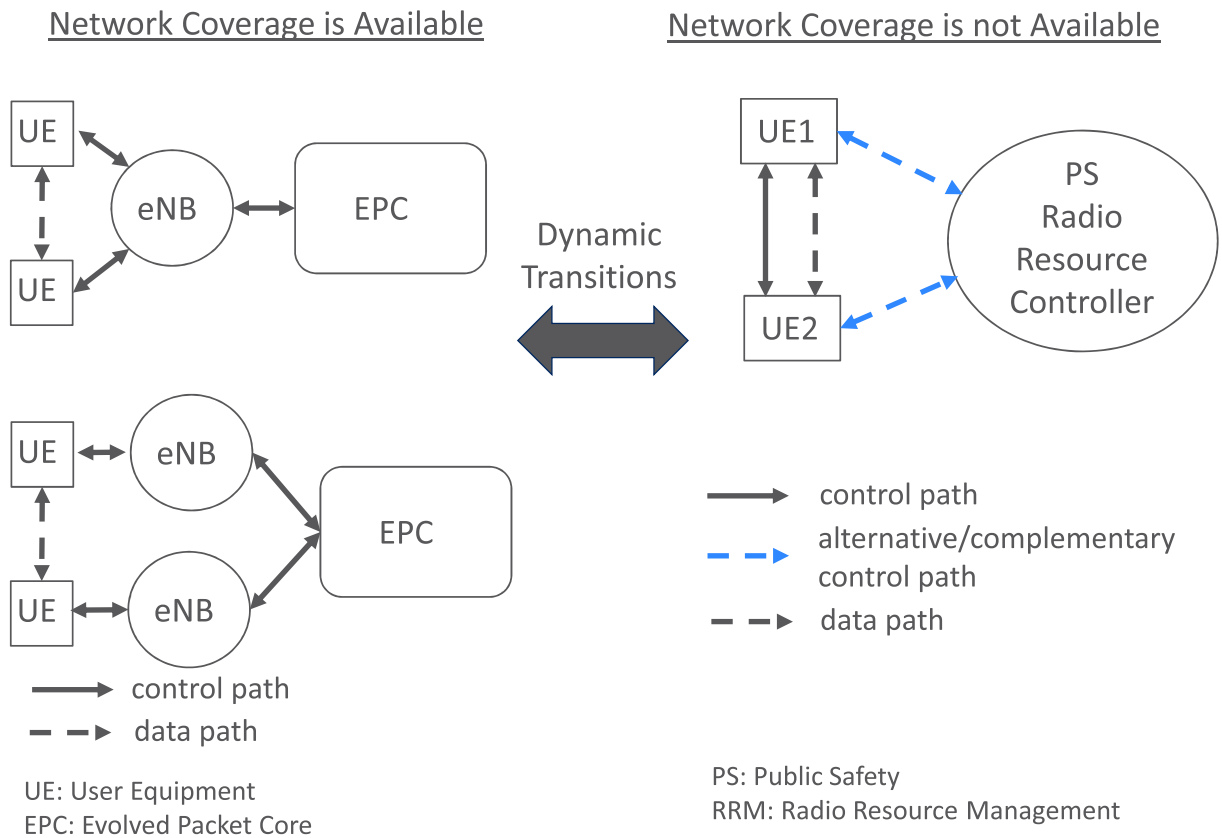
FIGURE 2. A key requirement for NSPS and PPDR systems is to cope with dynamic transitions between situations in which network coverage is available (left) and in which network coverage is not available (right). In this latter case, public safety UEs should be able to implement radio resource management and other functions of the network and thereby ensure graceful degradation when the cellular infrastructure becomes dysfunctional. If the public safety radio resource controller is implemented as a separate entity (right), an alternative/complementary control path established through this entity can help to manage radio resources for the D2D communications [8].

cellular infrastructure. Typically, but not always, the CH implements the role of SS. For example, if the CH is outside of a cellular BS coverage, but a cluster member is under cellular coverage, that member can act as a SS, relaying synchronization reference to the CH.

- *Radio Resource Management (RRM) Information Source (IS):* The RRM IS provides the CH with RRM information, such as restrictions on the usage of certain resources within the cluster, maximum transmit power level, or preferred frequency channels to use. Similarly to the SS role, the CH typically, but not always, implements the role of the RRM IS.
- *Slave:* The Slave UE's role is similar to that of an underlaid UE under network coverage. For example, if two slave UEs outside network coverage are D2D-capable, they may engage in D2D communications under CH assistance, similarly to the base station assistance in the underlay concept. UEs without CH, SS, or RRM capabilities can only become slaves in a cluster.

The roles of CH, SS, RRM IS, and slaves are illustrated in Figure 3. In the case of the left-hand-side cluster (a), the CH is under network coverage and obtains synchronization reference and RRM information from a cellular BS. In this case, the CH node takes the responsibility of synchronizing and managing the cluster, similarly to a cellular BS. In the

case of the lower right-hand-side cluster (b), the CH node is out of network coverage, but a cluster member is under network coverage. This cluster member acts as a SS and RRM IS that relays synchronization and RRM information from the cellular BS to the CH. Finally, the rightmost cluster (c) is entirely outside of network coverage. In this case, the CH autonomously acts as SS and RRM IS and manages the cluster that is isolated from the cellular network and from other clusters. From the perspective of the slaves, the CH acts analogously to a base station in terms of owning and managing radio resources including licensed spectrum that allows the cluster to operate in spectrum licensed for public safety.

B. SYNCHRONIZATION AND RADIO RESOURCE MANAGEMENT

LTE cellular networks may be deployed both with and without inter-cell synchronization as global time synchronization across multiple cells may be cumbersome. Therefore, all UEs within the same cell have the same time reference, although this may not hold for UEs in different cells. This aspect is retained in the proposed CH-based scheme. In other words, our proposal for out-of-network-coverage support is not based on global synchronization, but rather on local synchronization islands defined by the clusters. It is interesting to note how the proposed approach enables a common
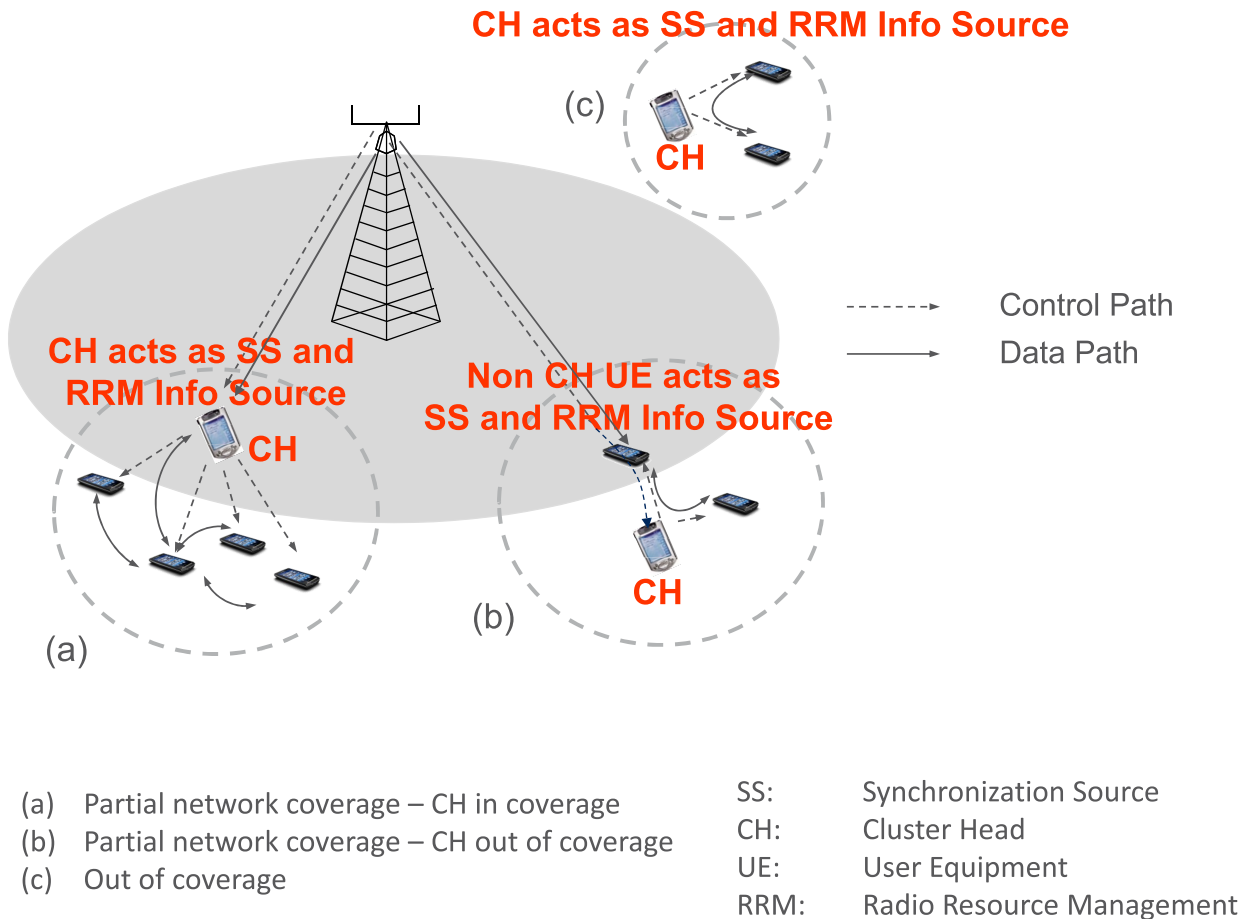
CH acts as SS and RRM Info Source

(c)

CH

CH acts as SS and RRM Info Source

CH

Non CH UE acts as SS and RRM Info Source

CH

(a)

(b)

- - - - → Control Path

———→ Data Path

(a) Partial network coverage – CH in coverage
(b) Partial network coverage – CH out of coverage
(c) Out of coverage

SS: Synchronization Source
CH: Cluster Head
UE: User Equipment
RRM: Radio Resource Management

FIGURE 3. Examples of the cluster head, synchronization source, and radio resource management information source entities in a geographical area with partial cellular network coverage ((a) and (b)) or without network coverage (c).

technical solution for D2D within and outside network coverage, which is desirable from a UEs chipset complexity and cost perspective.

With clear similarity to cellular LTE, NSPS-enabled UEs must be able to search for clusters in their proximity and eventually synchronize to the most suitable one. We propose that CHs broadcast synchronization signals similarly to how LTE BSs transmit primary and secondary synchronization signals (PSS/SSS), with the twofold objective of enabling channel quality measurements for cluster selection and providing a local synchronization reference. Additionally, CHs may provide basic RRM functionalities for tasks such as assigning radio resources to the associated slave UEs and managing interference and resources in a more centralized way. Naturally, whenever a cellular network (a BS) is detected, the UE associates with it with higher priority than with clusters.

Due to the limited coverage of the clusters as compared to BSs, it is desirable to enable inter-cluster discovery functionalities for proximity awareness. This can be achieved by providing the beacons with reference signals suitable for efficient asynchronous detection, similarly to how cellular UEs search for synchronization signals in (asynchronous) LTE deployments.

For direct data communication, on the other hand, it is convenient to require common synchronization between the transmitter and receiver(s) in order to reuse the efficient LTE communication procedures and protocols. When both the transmitter and receiver are associated with the same cell or cluster, they are immediately able to directly communicate synchronously. A less trivial scenario occurs when the receivers are not in coverage of the same cell or cluster of the transmitter. In such cases, the transmitter may temporarily take the CH role, limited to the duration of the data transmission and to the interested receivers, and provide local synchronization to its receivers.

Figure 4 provides examples of cell and cluster associations for a number of different scenarios. The figure clearly shows the commonality between the solution for cellular networks and hybrid/no coverage scenarios due to the similar roles of CHs and BSs.

C. CLUSTER HEAD ELECTION

An important detail of the CH concept is the definition of the rules upon which UEs autonomously take the CH role. CH selection algorithms for ad-hoc networks have long been a topic of research; see [10] and the references therein. An efficient system is characterized by a minority of UEs acting
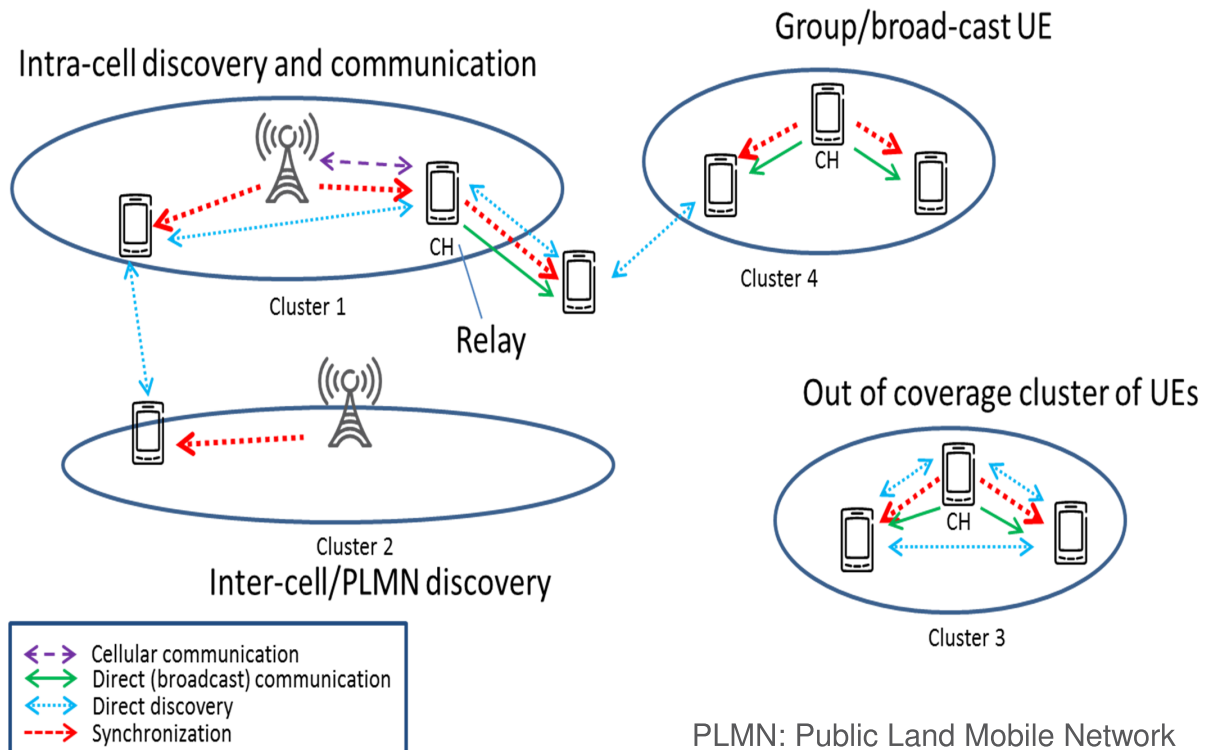
FIGURE 4. An illustrative example of how synchronization is provided in a scenario with four clusters supporting intra-cell discovery and communication, inter-cell Public Land Mobile Network (PLMN) discovery, group communication, and out-of-coverage communication. Notice that in the cases of direct discovery when both direct D2D and infrastructure based communication is possible, so called *mode selection* algorithms select D2D or cellular communication mode [2], [3].

as CHs, while most UEs either camp on a cell or on a cluster associated with a CH in order to reduce energy consumption and interference associated with synchronization signal transmission and detection. In our design, PS UEs may assume the CH role autonomously on an 'as needed' basis controlled by a CH selection algorithm that will be described in Section V. Once the CHs are selected and clusters are formed, the notion of out-of-coverage refers to a situation in which a UE cannot connect either to a cellular BS or to a CH.

Some examples of when CH-capable UEs may start acting as CHs in Figures 1 and 3 by running the CH selection and cluster formation (grouping) algorithms of Section V include:
- a PS UE that is out of BS and CH coverage;
- a PS UE that senses that another UE is out of coverage and needs a CH to which it can connect;
- a PS UE that moves out of the coverage of a BS and CHs and elects itself as CH;

As we will see in the performance analysis section, device discovery and CH election depends critically on the management of so-called peer discovery resources (PDR) [11], [13] that are used for transmitting and receiving beacon signals.

D. CLUSTERING AND UE MOBILITY
As pointed out in [10] and subsequently by [15] a major challenge in the clustering based system design is the management of clusters in the presence of UE mobility. To this end, it has been shown that explicitly taking into account

node mobility in the process of selecting CHs and associating slaves with CHs are beneficial in high mobility scenarios. Specifically, [10] demonstrated that in order to avoid frequent CH changes, it is desirable to elect a CH that does not move quickly. For example, a cellular BS may be a more suitable CH than a fast moving hand-held device even if the received reference signal or beacon signal strength alone would dictate otherwise. We refer to the detailed algorithm descriptions and investigations related to highly mobile scenarios in clustering systems in [10] and [15].

IV. PROTOCOL ARCHITECTURE ASPECTS
A UE that is capable of D2D communication must support a new UE-to-UE interface in addition to the UE-to-network interface. The new UE-to-UE interface protocol stack is used for all D2D signals, messages and data exchanged directly between UEs for the purpose of, e.g. peer discovery, synchronization, user data transfer and RRM control. This interface is a derivative of the UE-to-network LTE interface, but also contains specific elements.

As part of the cluster-based communication, control plane connections are established between the CH UE and all UEs being slaves in the same cluster. These control plane connections correspond well to the control plane connection established between a UE and the network when a UE under network coverage enters connected mode and used for similar purposes including bearer management and RRM [3].
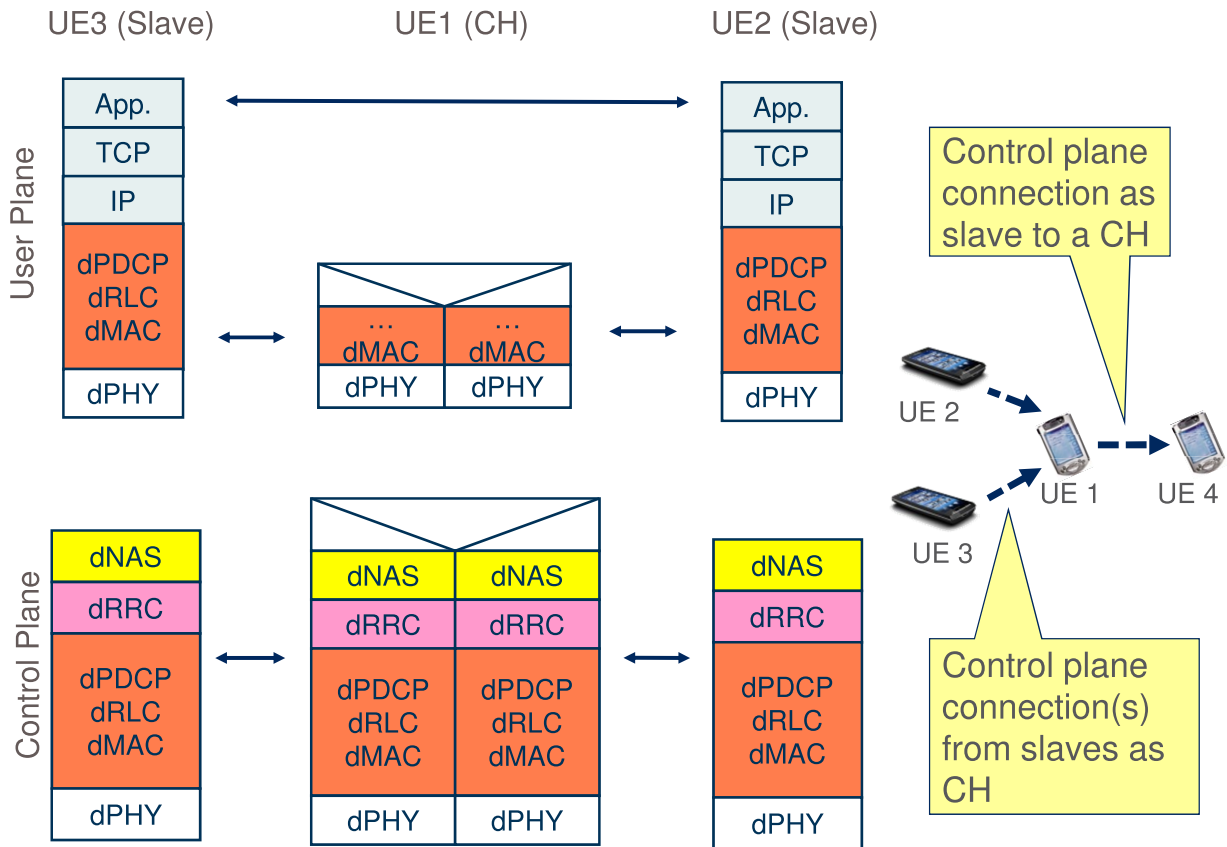
FIGURE 5. An example of control plane associations to support cluster based communication in a scenario involving 4 UEs (right). The detailed protocol stacks for the user and control planes are shown on the upper and lower left part respectively. The cluster arrangement at the right hand side of the figure is an example of the outcome of CH selection and clustering algorithms detailed in Section V.

The right part of Figure 5 illustrates, using an example of four UEs, control plane connections used to support cluster based D2D communication outside network coverage. Each peer control protocol entity communicating over a given UE-to-UE control plane connection takes one of two different roles. One entity takes the slave role and the other takes the CH role. The slave role corresponds to the role of a UE in the UE-to-network interface, while the CH role corresponds to the role of a network.

In Figure 5, UE1 has been selected as the CH by both UE2 and UE3 and serves control plane connections, using the CH role, from UE2 and UE3. Moreover, in this example, while UE1 has been selected as CH by UE2 and UE3, UE1 itself selects UE4 as CH. Therefore, UE1 establishes a control plane connection to UE4, using the slave role. Thus, a CH-capable UE (e.g. UE1 of Figure 5) may be CH and slave simultaneously as illustrated by the right hand side of Figure 5. In this way, control plane connections, as well as user data transfer, between clusters are made possible.

In the left part of Figure 5, the protocol stacks for cluster-based D2D communication are illustrated. In this example, UE1 has been selected as CH by both UE2 and UE3. To realize the control plane connections (lower left) established between UE2 and UE1, as well as between UE3 and UE1, derivatives of the corresponding UE-to-network LTE protocols are used. These derivatives are here

named D2D radio resource control and non-access stratum (dRRC and dNAS), respectively.

In the user plane (upper left), UE1 may serve as a relay node between UE2 and UE3 in case a direct radio link between UE2 and UE3 is not possible, due to, for example, UE2 and UE3 not being in the coverage area of one other. The layer 2 protocols for both the user and control plane are derivatives of the corresponding UE-to-network interface LTE protocols. These derivatives are here named D2D packet data convergence protocol, radio link control, medium access control and physical layer (dPDCP, dRLC, dMAC and dPHY), respectively.

The proposed architecture is part of the European 5G research and development project METIS that is currently developing technology components to support D2D communications in emergency situations [14].

V. PERFORMANCE ASPECTS

Clustering algorithms for multi-hop packet radio, wireless sensor and adhoc networks have been the subject of much study; see [10] and its references. More recently, the work by Zhe Li [11] evaluated the impact of network assistance on the performance of D2D discovery algorithms in terms of discovery probability, discovery time and consumed energy, while the work by Yufeng proposed a clustering based approach to meet NSPS requirements [15].
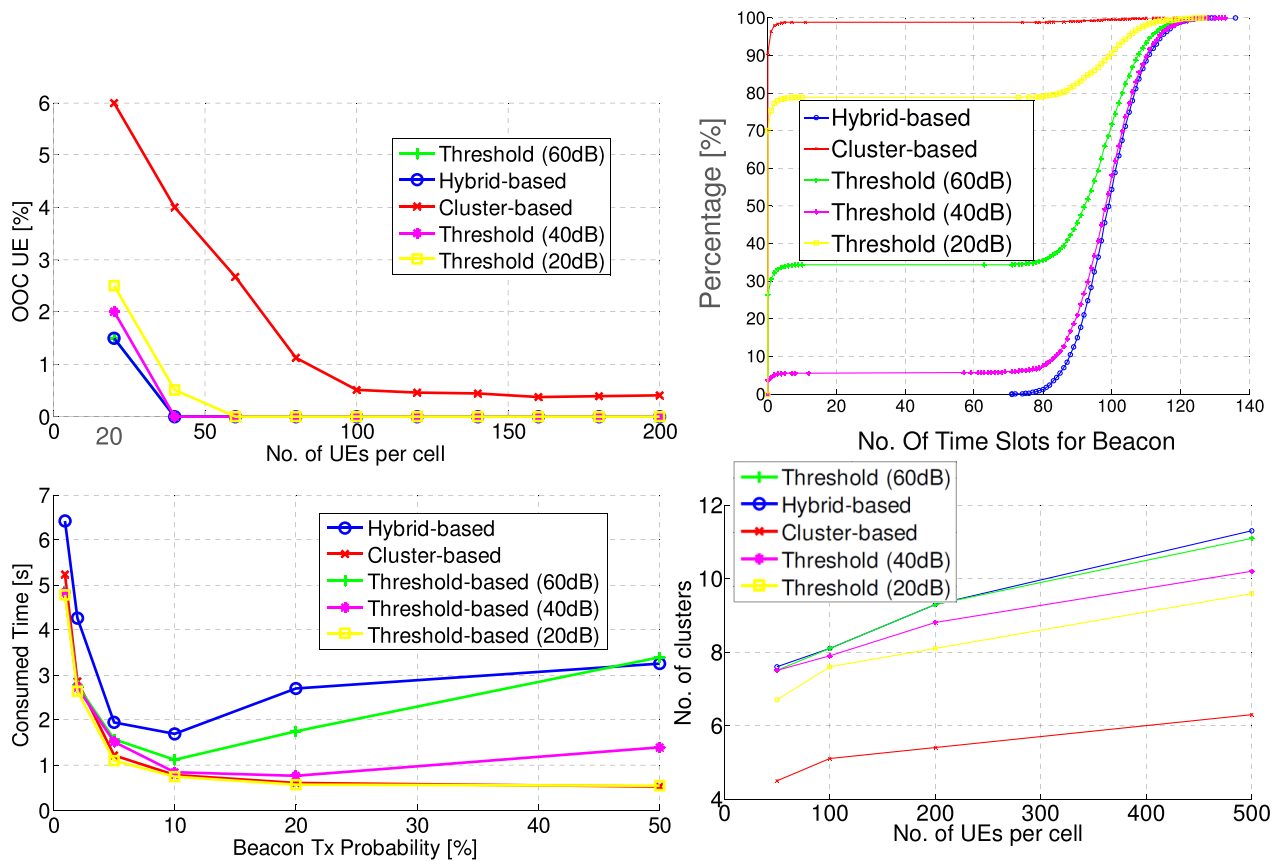
FIGURE 6. Performance metrics of interest in cluster based communications: percentage of UEs out of CH coverage (upper left), the time needed for organizing clusters (lower left) and the CDF of the number of required time slots for active beacon transmissions (upper right). The number of clusters formed depends on the cluster formation algorithm and the number of UEs in the geographical area. This figure shows the trade-off between the out-of-coverage probability and the cluster formation time. This trade-off can be controlled by the clustering algorithms that affect the cluster formation time, required number of time slots for beacon transmissions and the number of resulting clusters (lower right) in the system.

[14, Ch. 3 and 6] describe discovery algorithms applicable for D2D communications, but the issue of managing clusters in mixed infrastructure supported and infrastructure-less scenarios is not covered. A code-based device discovery protocol, which is applicable for not only device but also proximity based service discovery is proposed and investigated in [14], without explicitly addressing the special requirements of NSPS situations.

The key aspects of clustering algorithms include CH selection (identification), association, and dissociation of nodes to and from CHs (grouping) and intra- and inter-cluster communication. CH selection and grouping are typically based on nodes broadcasting so-called *beacon* signals on peer discovery resources (PDR) [3].

When adhoc networks interwork with the cellular infrastructure or public safety UEs, traditional clustering algorithms must be extended so that they account for the capabilities of cellular base stations, provisionally deployed access points, or specially designed user equipment with high transmission power. CH selection, grouping strategies, the selection of PDRs, beacon signaling periodicity, and the setting of beacon transmission probability in each time slot and beacon transmission power represent a tradeoff between energy and spectral efficiency and the capability

of dynamically reconfiguring the network due to mobility, changing radio conditions, and nodes joining and leaving clusters [10]. To gain insights into clustering algorithms, we use system simulations to study various clustering algorithms. Here we focus on the aspect of out-of-coverage probability, convergence time and the number of required time slots for beacon transmission (energy efficiency) and point at ongoing work for further results.

A. ALGORITHM DESCRIPTION
Our clustering procedure consists of two phases: CH selection and cluster formation (grouping).

1) PHASE 1-CH SELECTION
During this phase, each PS UE continuously broadcasts beacons containing its identifier and its predefined capability metric using a single PDR. In this context, *continuous* beacon transmission means that a PS UE transmits a beacon in every time slot that is defined as a PDR. Alternatively, a PS UE may transmit with a certain beacon *transmission probability* that helps reduce the overall beacon collisions in the system [11]. The capability metric is precomputed using a weighting function that combines the device capabilities such as maximum transmit power, battery level, and availability of

network coverage, thus giving priority to cellular BSs to take the CH role. As mentioned in Subsection III-D, this capability metric can also include UE mobility, although this approach is not examined further in this paper.

In parallel, every device, when receiving and successfully decoding a beacon, stores the identifier of the sender and the corresponding metric. This phase allows PS UEs to build knowledge about their neighbors' metrics. Next, the devices having the highest metrics identify themselves as CHs, while the remaining PS UEs with lower metrics identify themselves as slaves.

2) PHASE 2-CLUSTER FORMATION (GROUPING)

In this phase, each non-CH device selects the appropriate CH and associates with it. For this stage, we evaluate three grouping schemes.

- *CH-Driven:* Only the CHs continue broadcasting beacons. This approach has the advantage of reducing the number of active devices competing for PDRs and thereby improving the SINR of received PDR within a given range and reducing the collision probability. In this case, however, some UEs may get out of coverage – that is they cannot establish a communication link with a BS or with a CH – even when they are in the proximity of a CH-capable UE (which is currently not assuming a CH role and has discontinued broadcasting beacon signals).

- *Hybrid:* Every PS UE (CHs and slaves) continues broadcasting beacons. UEs that receive these beacons select the strongest PS UE and send a notification. Upon receiving such a notification signal, a PS UE that is not selected as CH in Phase 1 becomes a CH. This approach better supports cluster reconfigurations by reselecting CHs, which increases the probability of a device being covered by a cluster. However, the drawback is the higher beacon load in the system, which increases the PDR collisions and thereby the discovery and cluster formation time in addition to the energy consumption.

- *Threshold-Based:* Our third clustering alternative takes into account the quality of beacon signals to estimate whether a PS UE is at the edge of a cluster. Specifically, if PS UE-A identifies itself as a slave in Phase 1, but the maximum signal it receives from any of the CHs (identified in Phase 1) is below a predefined threshold (e.g., SNR = 20, 40, or 60 dB), PS UE-A considers itself to be located at a cluster edge with respect to the existing CHs and so it continues sending out beacons in order to provide coverage for nearby slaves. After this step, the threshold-based approach is similar to the hybrid approach. This prevents slaves with limited capabilities from remaining isolated and ensures high-quality links between each CH and its slaves.

B. PERFORMANCE MEASURES OF INTEREST

The efficiency of CH selection and clustering algorithms is characterized by three metrics: the coverage ratio, which reflects the percentage of UEs that successfully connect to a CH (receives an SINR above a predefined discovery threshold), the average time needed for a slave to discover its corresponding CH; and the energy required for the clustering procedure. Assuming that a beacon transmission consumes more power than a reception, here we only consider the number of time slots when the UE is active for beacon transmission; in other words, in our model the energy consumption is proportional to the number of the active slots for beacon transmissions.

C. NUMERICAL RESULTS

We consider an area equivalent to a cellular system with inter-site distance (ISD) of 500 m, in which equal loads of CH-capable UEs and CH-incapable UEs are uniformly dropped. Note that the ratio of the UEs that actually become CHs depend on the parameters of the CH selection parameters and the cluster formation algorithm (see Figure 6.) The path loss between devices is modeled using the 3GPP Home eNB model with one building per sector and and assuming that 35% of the users are indoor.

To gain insights into the tradeoff between the performance measures of interest for the D2D clustering procedure, we simulated the performance of the proposed alternatives for different densities and traffic loads: we considered UE loads ranging from 20 to 500 UEs per cell and beacon transmission probabilities from 0.1 to 0.5.

First, the estimation of the number of UEs covered by at least one CH shows that, using the CH-Driven algorithm, some UEs remain out of coverage (see the upper left graph in Figure 6), particularly in case of a sparse network (few CHs). In contrast, both the hybrid and the threshold based approaches (with proper threshold) provide full coverage. Nevertheless, when observing the time required for the clustering, the convergence of the hybrid algorithm seems to be the slowest (lower left graph in Figure 6). This is explained by the high number of UEs transmitting their beacons signals, which exceeds the number of available discovery resources and results in high collision risk at every frame, leading to a slower convergence. The result on the number of required time slots used for beacon transmission (that translates directly to overall energy consumption) is shown in the right-hand-side graph of Figure 6.

The results show that the CH-driven approach is more energy-efficient (in terms of the time slots needed for beacon transmission until convergence) than the hybrid approach, where every potential CH broadcasts its beacons, particularly when a high beacon transmission probability per time slot is chosen. As shown above, however, this energy efficiency comes at the price of the degradation of the coverage ratio. On the other hand, by considering the signal strengths between PS UEs in addition to their capability, the threshold-based approach can handle the tradeoff between energy efficiency and convergence ratio. For instance, the selection of a low transmission threshold value (20 dB) guarantees a near full coverage in all scenarios (low and high densities)

within similar delays as the CH-driven algorithm, but with considerably lower energy consumption. The comparison of our proposed CH selection and cluster formation algorithms with similar algorithms is left for future research [11], [15].

VI. CONCLUDING REMARKS AND OUTLOOK

There is a growing interest in providing broadband telecommunication services in national security and public safety situations. Building on the commercial success and economy-of-scale of LTE systems is attractive both for users and service providers; therefore, the 3GPP is currently studying enhancements to the LTE standard in order to better support NSPS scenarios, such as by supporting operation in absence of network coverage. Furthermore, a key aspect for LTE-based NSPS is to take advantage of the fixed infrastructure when available in order to further enhance the performance compared to network-less operation.

To this end, we proposed extending the concept of network-assisted (underlay) D2D communications to situations in which the cellular coverage is partially or completely missing. Part of this concept is to dynamically form clusters by means of cluster head nodes that can be implemented by adhoc base stations as well as handheld devices and to integrate such clusters in cellular networks where available. We reviewed some of the synchronization, protocol, and algorithmic aspects that need to be in place before broadband NSPS services become commercially available. Clearly, the interplay between the adhoc and cellular elements, radio resource management, as well as quality of service, mobility, and security aspects in evolving multioperator scenarios require further research.

ACKNOWLEDGMENTS

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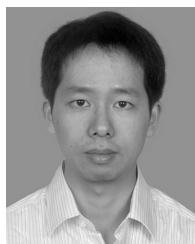
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