Clustering Schemes for D2D Communications Under Partial/No Network Coverage

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***Abstract*—Device-to-device (D2D) communications as an underlay to cellular networks can not only increase the system capacity and energy efficiency, but it can also enable national security and public safety (NSPS) services. A key requirement is to provide access to cellular services when the network is available and maintain local communication in the (partial) absence of the infrastructure. In this paper we propose and compare clustering schemes that are applicable for integrating D2D communications into cellular networks such that communication services can be maintained when the cellular infrastructure becomes partially dysfunctional. Our results show that there is a trade-off between coverage, energy efficiency and cluster formation delay and this trade-off can be handled by our proposed threshold-based clustering scheme.[1]**

Keywords—D2D; Device Discovery; Clustering

I. INTRODUCTION

Device-to-device (D2D) communications as an underlay to cellular networks can increase the system capacity thanks to the reuse and hop gains and improve the peak rate due to the proximity gain [1], [2]. D2D can also reduce the latency and serve as a technology enabler for proximity-based social networking [3], [4]. Recently, D2D communications have been proposed as a key technology enabler for national security and public safety (NSPS) services, as D2D has the potential to operate both under network coverage and in the absence of the cellular infrastructure [5].

Designing system solutions that provide broadband access to core network and Internet services when the access infrastructure is intact and maintain local communication capabilities when parts of the wireless access network becomes dysfunctional is a challenge for a number of reasons. First, users expect a graceful degradation between a fully operational radio access network (RAN), partially damaged (maybe a few base stations affected) network and a completely dysfunctional RAN as can be the case in an earthquake situation. Secondly, due to device mobility, the system must be able to handle dynamic transitions between operational and non-operational segments and maintain local communication (proximity) services in a close to seamless fashion [6].

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Since network-assisted D2D communications take advantage of the presence of the cellular infrastructure, we propose to build on the D2D underlay concept, but extend it in such a way that it allows infrastructure-less operation. To this end, we propose an approach in which high end capability user equipment (UE) can take over some of the RAN functionalities when one or more cellular access point or base station (BS) become dysfunctional. Such functionalities include providing synchronization signals and acting as a *cluster head* (CH) that has similar role in NSPS situations as a BS has in a fully functional RAN.

The concept of clustering is well known and a large number of clustering algorithms applicable in multi-hop packet radio and ad-hoc networks operating in unlicensed spectrum have been studied, see for example [7]. The key aspects of clustering include CH selection (identification), association, and disassociation of nodes to and from CHs (grouping) and managing intra- and inter-cluster communications. However, when ad-hoc networks have to interwork with the cellular RAN or CH nodes that can take over some RAN functionalities, the traditional clustering algorithms need to be extended. In particular, the capabilities of cellular base stations, provisionally deployed (fire brigade) access points or specially designed user equipment with high transmission power need to be taken into account in all aspects of clustering.

In this paper we study three clustering schemes by means of system simulations. Each scheme consists of a cluster head selection and a cluster formation (grouping) phase, but the grouping phase differs in terms of beacon signal transmission strategy. These strategies represent a trade-off between complexity, energy consumption, beacon collision probability and cluster formation (discovery) time. As a result of our insights, we propose a threshold-based cluster formation scheme in which not only elected CH nodes but also cluster edge nodes broadcast signals to facilitate the dynamic regrouping of clusters hence ensuring a balance between cluster formation time and energy consumption.

The next section describes our system model. Section III discusses the clustering schemes applicable in the mixed cellular ad-hoc environment, while Section IV presents numerical results. Section V highlights our main conclusions.

II. SYSTEM MODEL

A. User Equipment Types

Recall that in the hybrid cellular/cluster based concept, the capability of nodes must be taken into account. The capability of a device (e.g. available transmit power, supported spectrum bands or synchronization or radio resource management capability) in combination with the availability of network coverage distinguishes two types of UEs:

- **Type-1 UEs** represent user equipment (UE) and devices capable of acting as cluster-heads (CH), controlling the D2D links and managing the resources usage among a group of D2D devices associated with it. For each of these devices a pre-computed *metric* is defined as a function combining the capabilities of the devices (CH capable or not, maximum power allowed), the remaining power level and the availability (presence) of network coverage. The reason for including network availability in the metric is to assign higher priority to devices under network coverage to form clusters and take advantage of the network assistance for managing D2D peers. This also means that each device has to upgrade its own capability when it gets under (or out of) network coverage that in turn may trigger a new clustering procedure.
- **Type-2 UEs** are devices that can only act as cluster *members* (slaves). Therefore, when out of coverage, they are controlled by appropriate type-1 UEs that they select as CH to assist them in establishing and managing D2D links in a similar fashion as a cellular BS according to the underlay concept. We assume that two type-2 UEs out of the coverage of a cellular base station or a CH node cannot communicate directly with one another, similarly to the situation of two legacy UEs or D2D capable UEs in the network assisted (underlay) concept being unable to establish a direct link when out of coverage[2].

In the proposed concept, only type-1 UEs are allowed to broadcast beacon signals for device discovery. Based on exchanged signals, some of these devices will designate themselves as cluster heads, while the remaining type-1 UEs and the type-2 UEs will join a cluster head and hence forming a cluster structure. More details on the clustering procedure will be described in Section III.

B. Discovery Model

In our scheme, a beacon signal is sent using a Peer Discovery Resource (PDR) defined in the form of OFDM Physical Resources Blocks (PRB) in, for example, the LTE-A frame structure. To ensure a low D2D discovery overhead, only certain frames are used for discovery (e.g. one frame every 10 LTE-A frames) and within each discovery frame a predefined number of PDRs are set aside for beacon transmission purposes (see [8] for more details about PDR design applicable in LTE).

Whether a device is discovered or not by another neighboring device is determined by the quality of received SINR measured from the beacon signal. Therefore, we use an SINR *threshold* as the criterion of device discovery: as long as the SINR measured at the receiving device (Rx_UE) from a given transmitter (Tx_UE) exceeds the discovery threshold, the Tx_UE is discovered by the Rx_UE. The value of the SINR threshold can be pre-defined depending on the decoding techniques used. In practice, quite low SINR (e.g. below 0 dB) signals can be decoded increasing the discovery coverage around the Tx_UE device. We also assume that the devices can decode different beacon signals in different frequencies simultaneously.

III. DEVICE CLUSTERING ALTERNATIVES

The clustering procedure consists of three main phases: the first step is to identify the nodes with the best capabilities to play the role of cluster heads. The second step is to select the appropriate cluster-head among all the potential ones. Finally, each device connects to the corresponding CH to build a cluster structure.

A. Cluster Head Identification

During CH identification, type-1 UEs use PDRs to continuously broadcast beacons that include the pre-defined metric. PDR collisions may occur which reduce the discovery range, slow down the discovery process and increase the overall energy consumption. To address this problem, we define a transmission probability *Ptx* controlling the beacon transmission of each type-1 UE. When transmitting, a type-1 UE randomly picks a PDR out of the available PDRs (see Figure 1 and [8] for further details).

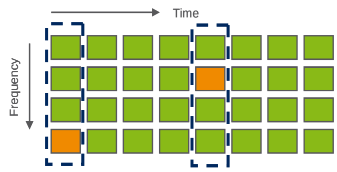

Fig. 1. For each time slot (one unit in the time dimension), each master decides to transmit or to listen with probability Ptx. If it transmits it picks a PDR from the multiple PDRs in the frequency dimension.

In parallel, every device, when receiving and successfully decoding a beacon, stores the identifier of the sender and the corresponding metric. Thus, type-1 devices learn the capabilities of neighboring type-1 UEs that allows them to elect the CHs, that is to delegate the controlling functions only to a few devices in order to make the D2D resource management simpler and more efficient. If no beacon signal is received during this phase the device will assume itself being out of coverage of any other type-1 UE and identify itself as a cluster-head.

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[2] Two UEs out of coverage may of course be able to establish a direct link using a technology operating in the unlicensed band. However, such solutions do not meet the requirements of, for example, the First Net, see [5], [6].

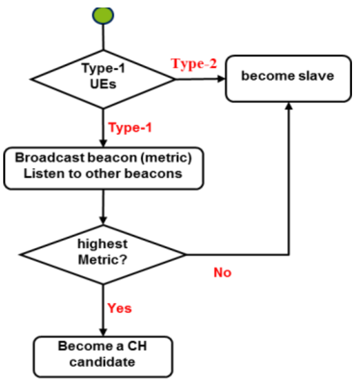

Fig. 2. Flow chart for CH-identification

Next, each type-1 UE compares its own metric with the metrics of its neighbors. The devices having the highest metrics consider themselves elected cluster-heads (CHs). Other type-1 UEs having lower metrics identify themselves as slaves (non-CH UEs) and they have to join one of the CHs in Phase 2 (see Figure 2).

B. Phase 2: UE Clustering

Each non-CH device has to select the appropriate CH and associate with it. This association is done based on the CH beacons that elected CHs broadcast. At this stage, depending on which nodes broadcast beacons, three grouping schemes are possible (Figure 3).

1. **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 (OOC) even when they are in the proximity of a CH capable UE. Also, according to this alternative once a device is identified as a CH, it is not allowed to be a slave of another CH which prevents inter-cluster communications even in case devices from two different clusters are close to one another.
2. **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.
3. **Threshold-based**: The 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 CHs and slaves.

C. Phase 3: Slave-CH association

After identifying the appropriate CH during phase-2, each slave sends a request to associate with its CH. If this request is accepted then the slave establishes a control plane connection to the CH which uses it to provide synchronization and to schedule the resource allocation for different D2D pairs. Another way to establish the slave-CH association is to let the slave follow the synchronization and the RRM information broadcasted by the CH.

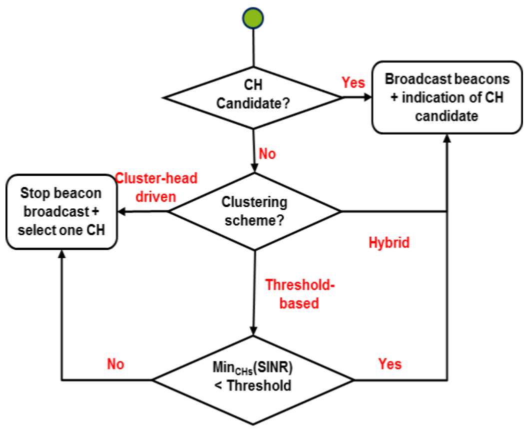

Fig. 3. Phase 2: Based on their types and the clustering approach used, the type-1 UEs decide to broadcast or not their beacons.

The rest of this paper is devoted to the evaluation of different clustering approaches. The goal is to find the balance between cluster coverage, the latency required for structuring the D2D network into clusters and the energy required for the clustering procedure.

IV. PERFORMANCES ANALYSIS

We consider an area equivalent to one cell in a cellular system with inter-site distance (ISD) of 500 m, in which equal loads of type-1 UEs and type-2 UEs are uniformly dropped. We assume that all devices operate in D2D mode and the path loss between devices is modeled using the 3GPP Home eNB model with 1 building per sector and 35% of the users being indoor. To gain insight into the tradeoff between the performance measures of interest for the D2D clustering procedure, we simulate the performance of the proposed alternatives for different densities and traffic loads ranging from 20 to 500 UEs per cell and beacon transmission probabilities from 0.1 to 0.5. The efficiency of different clustering approaches is evaluated using the following metrics.

1) Convergence Ratio refers to the percentage of UEs that are able to connect to the right CH by receiving at least one beacon with an SINR above the discovery threshold.

2) Convergence Time estimates the time needed for a slave to select its corresponding CH.

3) Energy Consumption is proportional to the number of the active slots for the beacon transmissions. Since beacon transmission consumes more power than a reception, we only consider the number of time intervals when Type-1 UEs are active for transmitting their beacons.

A. Convergence Ratio Vs. Convergence time

The coverage of a cluster is defined as the area where the beacon signals of the CH reach all the devices with SINR values above the discovery threshold so that they can correctly be decoded. The estimation of the number of UEs covered by at least one CH shows that only using the cluster-head driven approach, some UEs remain out of coverage, especially when the density of devices is low. In contrast, the hybrid and the threshold-based approaches provide full coverage by allowing a higher number of cluster-head capable UEs to broadcast their beacons as shown in Figure 4. In particular, by setting low transmission threshold, the third scheme is able to guarantee coverage for all UEs with a minimum total number of clusters (see Figure 5).

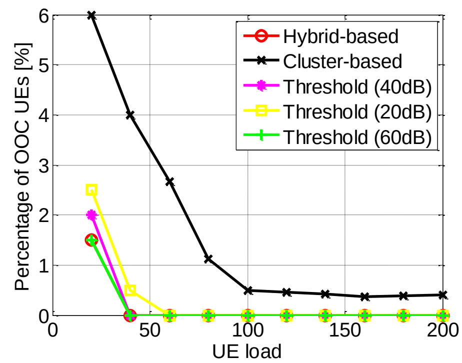

Fig. 4. Number of UEs out of cluster-coverage: in cluster-driven approach only few nodes are desginated as CHs without any consideration of the signal strengths received from these CHs, some UEs remain out of coverage as opposed to hybrid and threshold-based schemes which guarantee full coverage.

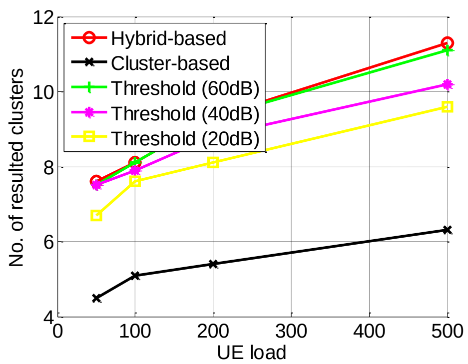

Fig. 5. The total number of clusters: Using the cluster-head driven approach only one-layer clusters are created as opposed to the hybrid and the threshold-based schemes where more clusters are formed by allowing inside is created inside one cluster.

However, when observing the convergence time in Figure 5, the hybrid clustering scheme seems to be the slowest one. This is due to the high number of type-1 UEs broadcasting their beacons at every frame which exceeds the discovery resources leading thus to a high collision risk. The same behavior is observed when the transmission threshold is set to a high value (60dB) increasing so the number of active devices in the system and competing for the discovery resources.

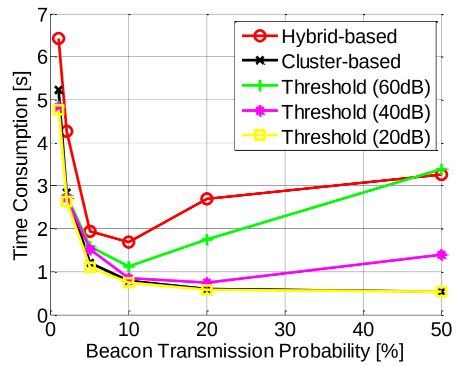

Fig. 6. Convergence ratio and convergence latency achieved by different clustering approaches with different system loads. When the beacon load is high, the collision risk becomes more important and reduces the discovery rate and increases the time required to form clusters between neigboring D2D candidates.

B. Energy Consumption

As mentioned above, the energy consumption is proportional to the number of the active slots for the beacon transmissions. The results in Figure 6 show that the cluster-head-driven approach is more energy-efficient compared to the hybrid approach, where every potential CH is broadcasting its beacons particularly when a high transmission probability is chosen. Nevertheless, as illustrated in Figure 4, this energy efficiency comes at the expense of reduced coverage. On the other hand, by considering the signal strengths between type-1 UEs, the threshold-based approach can ensure a balance between the energy consumption and the convergence ratio. For instance, the selection of appropriate transmission threshold value guarantees high coverage within relatively short delays while consuming considerably lower energy consumption compared to the cluster-based scheme.

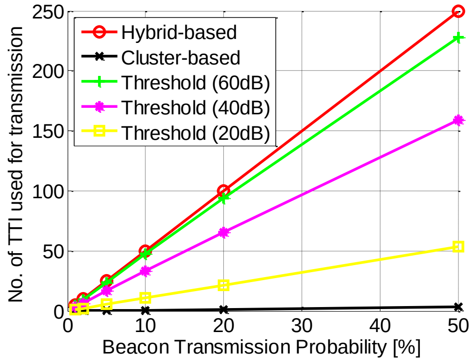

Fig. 7. Energy required for discovery and clustering is lower when only few nodes (CHs) are allowed to transmit their beacon signals.

C. *Inter-cluster Interference*

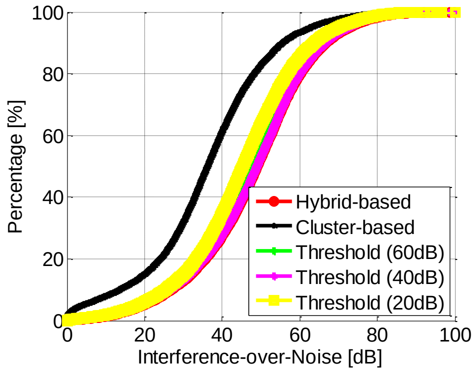

Fig. 8. Inter-cluster intereference: in cluster-driven approach no inter-cluster communication is allowed therefore less devices are affected by inter-cluster intereference, whereas more devices experience intereference in the hybrid and the threshold-based approaches due to overlapping areas between clusters.

Both the hybrid and threshold-based approaches enable inter-cluster communication by allowing all type-1 UEs or UEs located at a cluster edge with respect to the existing CHs, respectively, to continues sending out beacons and provide coverage for nearby slaves. This introduces inter-cluster interferences which require coordination in particular in cases of high number of CHs. However, the selection of low beacon transmission threshold (20dB) reduces the overlapping areas between independent clusters and thus decreases the inter-cluster interferences. This observation is confirmed by measuring the number of devices suffering from inter-cluster interferences as indicated in Figure 7. The threshold-based clustering is the best approach to achieve a balance between the cluster coverage and the inter-cluster interferences. More precisely, the overlapping areas between clusters should be large enough to provide coverage for all the devices but not too small to generate high interference between clusters.

V. CONCLUSIONS

There is a growing interest in providing broadband communication services in national security and public safety situations. Therefore there is an interest in designing systems that can take advantage of the fixed infrastructure when available and are able to maintain local communication services when the infrastructure is damaged. To this end, we have 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 ad-hoc base stations as well as handheld devices and to integrate such clusters in cellular networks where available. In particular, the grouping procedures allow a device to discover and connect to a cluster head device capable of taking over some of the functionalities of cellular base stations. The proposed approaches were implemented in a system simulator and tested for different users' densities and traffic load. The results indicate that a low complexity threshold-based clustering scheme based on existing measurements can balance between energy consumption, coverage and cluster formation speed.

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