Coordinated in-band ad-hoc transmission underlying cellular networks

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Abstract— **In this article ad-hoc communications underlying cellular networks is studied. Two branches of usage cases, which lead to two modes of operation, are analyzed. We propose a coordinated in-band scheme where the ad-hoc communication uses the same licensed band operating the cellular networks and is under the control of cellular network operators. We show that the interference resulting from in-band ad-hoc transmission can be effectively managed by proper scheduling. The spectral efficiency gain is substantially increased using the proposed scheme.**

I. Introduction

Local multimedia services, including local multimedia sharing, local gaming, etc. are getting more and more popular. Their increasing demand for higher data rate presents a challenge in cellular networks, due to the limit of licensed band. Comparing to conventional DL/UL transmitting mode in cellular networks, direct ad-hoc short-range transmissions appear to be a more natural solution to local data transfer. Incorporating ad-hoc communications into cellular networks, therefore, can be a promising way to complement the existing cellular networks with efficient local communications, and to make a better use of the spectrum. Another interesting scenario that can be introduced by this hybrid network architecture is the usage of mobile as a relay. It might offer a flexible and cheap alternative to the current Femto cell or fix relay techniques for cellular capacity enhancement and cellular coverage extension.

Aiming to support various high-speed low-cost local services, ad-hoc technologies are taking off in several wireless standards. Examples are Bluetooth in wireless personal area networks (WPANs), and Wi-Fi Direct in wireless local area networks (WLANs). Recently there has been a lot of active research [1-3] on the integration of ad-hoc technologies into the next-generation wireless communication systems such as LTE and WiMAX (notably the 802.16n task group which deals with direct communication, mobile discovery, mobile forwarding, and standalone networks, etc.).

The ad-hoc transmissions underlying cellular networks can operate either out-of-band or in-band. Out-of-band usually refers to usage of unlicensed band such as ISM band or TV whitespace, and it might also refer to pre-allocated licensed band. The unlicensed band has the advantage of being free, but it also has the drawback of uncontrolled interference and lack of global synchronization [4]. While the aggregate spectral efficiency on using pre-allocated licensed band might be not high enough to justify the cost of licensed spectrum.

When operating in-band, ad-hoc transmission can use DL and/or UL resources and might interfere severely with DL and/or UL cellular transmission. It's required that the two parts interwork smoothly with minimal or no negative impact on the cellular part of the network. There are several ways of in-band ad-hoc communication to coexist with cellular networks. One possible way is self-organization, in which ad-hoc sessions are set up and configured autonomously by UEs, without the intervention of cellular networks. Interference avoidance in self-organizing networks is still quite challenging. Dynamic spectrum sensing, for example, can allow ad-hoc UEs to opportunistically access the channel with limited interference to cellular users. However, performance of the ad-hoc part highly depends on the actual utilization of spectrum. Moreover, this method requires continuous spectrum sensing, which puts high complexity on the UE side. Another way to limit interference from in-band ad-hoc communication to cellular communication is by limiting the transmitting power of self-organizing networks, applying techniques such as spreading spectrum. This method doesn't require high complexity radio in UE, but the data rate of ad-hoc communication is rather limited due to the low transmitting power.

Alternatively, ad-hoc communication can be controlled by the cellular part, in a centrally coordinated way. The decision of ad-hoc session setup can be optimized by a central coordinator and the data interference can be minimized by coordinated scheduling and power control techniques. It is proposed that high gains in aggregate spectral efficiency may be achievable. [1,2] argue that the hexagonal hybrid networks with in-band multi-hop ad-hoc relaying can achieve up to a 200% increase in the uplink capacity compared to pure cellular networks, and a 70% increase in the downlink. [5] shows the almost three-fold cell capacity increase by enabling indoor local communication reusing cellular TDD resources.

In this paper, we investigate a coordinated scheme for in-band hybrid cellular ad-hoc networks. Our study uses LTE FDD cellular networks as the baseline. We distinguish two modes of ad-hoc operation: Point-to-Point (P2P) and UE-as-a-Relay (UEaR), according to their different usage scenarios underlying cellular networks. For each mode of operation, benefits and requirements of coordination are discussed. For a dense P2P deployment scenario, we detail a scheduling method which is interference-aware and can exploit the multi-user diversity of cellular networks to increase the spectral

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efficiency. The simulation results show significant performance gains compared to pure cellular networks.

This article is organized as follows. Section II presents two modes of operation: P2P and UEaR, for ad-hoc communication underlying LTE cellular networks. For both modes of operation, we analyze coordination issues in two main stages: ad-hoc session setup and data transfer for ad-hoc links. In addition, two-hierarchy coordination is proposed for P2P transmission. A centralized scheduling method based on the proposed two-hierarchy coordination structure is detailed in section III. Numerical results are illustrated in section IV.

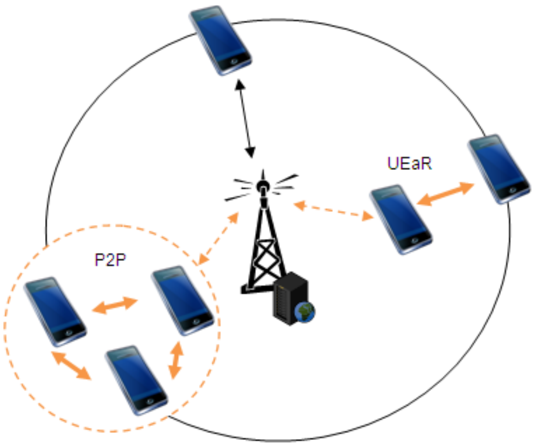

Figure 1. Two forms of UE-UE communication

II. COORDINATED IN-BAND UE-UE COMMUNICATIONS

The ad-hoc communication underlying cellular networks can be distinguished in two forms: Point-to-Point (P2P) and UE-as-a-Relay (UEaR), as illustrated in Figure 1. In the case of P2P, the pair of UEs involved is endpoints (source and sink) for communications. Instead of passing all the messages through eNBs in a traditional UL and DL path, the data transfer could happen directly between a local UE pair. While in form of UEaR, one or more UEs are acting as relays to form a multi-hop connection between an eNB and another UE. Therefore, unlike the P2P form, at least one of the UEs in a given pair is not an endpoint. Such relaying may be beneficial for UEs that have poor connection to eNBs due to shadowing or blocking. For either UE-UE scenario mentioned above, tight integration with cellular networks could be a possible way to maintain seamless QoE and consistent QoS. The central coordinator (eNBs and core networks) can play an important role in two main tasks: session setup and resource allocation. The following subsections describe how the session setup and data interference mitigation can be realized by a central coordinator.

A. *Session Setup*

In an uncoordinated scheme, based on biased knowledge of UE-UE links only, the uncoordinated ad-hoc UEs might encounter difficulties to evaluate the gain and the cost of UE-UE session initiation and might therefore initiate the UE-UE session in some unfavourable conditions. While in a coordinated scheme, the decision can be optimized by careful evaluation and comparison. A UE-UE session can be setup when its performance overweights that of conventional DL/UL mode of transmission, and can be released if the UE-UE link fails. On the failure of UE-UE link, either DL/UL mode is resumed, or in UEaR mode, a relay reselection procedure can be conducted. Such a central coordinator enables a reasonable fallback between ad-hoc mode and DL/UL mode, which provides the possibility to maintain seamless QoE.

On the other hand, the evaluation of UE-UE link, which involves the neighbor discovery, although can be achieved in uncoordinated way as well, could be greatly simplified when a central coordinator exists. The neighbor discovery is essential in the evaluation of UE-UE link in order to verify that a UE pair is within direct communication range of each other. In P2P case, it can happen that the transmitting UE has a specific destination UE to communicate to, and it wants to detect if this destination UE is within the direct communication range or not. While in UEaR case, an out-of-range UE might try to discover all the neighboring UEs within the range in order to ask for relaying. In self-organizing ad-hoc networks, one way of neighbor discovery is by using periodic beacons [6] on a shared channel, such as in WPAN(IEEE 802.15.3). Another way is by detecting neighbors' activities [5]. In contrast, the central coordinator could facilitate the neighbor discovery as the cellular part possesses overall knowledge of the network. In a P2P case where the transmitting UE has a specific destination UE to communicate to, the intervention of a central coordinator could prevent the neighbor discovery procedure for cases that source and destination UEs are obviously out of direct communication range of each other (in different cells far apart). Knowledge of UE positions can come from the analysis of source and destination Cell-ID, Round Trip Time (RTT) and Angle of Arrival (AoA), etc.[10] in central cellular networks. Moreover, as source and destination UEs are known to the core network, only these two UEs need to be involved in the neighbour detecting procedure, and other UEs can be exempted from 'stop and listen'. Similarly in UEaR case, when a target UE becomes unsatisfied, with the UE positioning capability, the central cellular network is able to recognize UEs which are geographically close to the target UE. Therefore involving only the set of nearby UEs in the neighbour discovery procedure can help avoiding unnecessary signalling and increasing network efficiency.

B. *Data Transfer*

Co-channel interference caused by in-band spectrum reuse is the most acute problem in heterogeneous networks. Therefore interference management is a key issue in scheduling. To minimize interference within a cell, resources of UE-UE transmission part and cellular transmission part can be scheduled jointly by cellular networks. The principle is to schedule mutually interfering concurrent transmissions on different frequency bands, whereas in order to maximize the spectral efficiency, resources reused should be allowed within the hybrid cell between isolated UE-UE transmissions and cellular transmissions. Spatial orthogonality can be enhanced with MIMO coordinated beamforming. For example, assuming that the CSIT (Channel State Information at Transmitter) of

UE-UE link is available at eNB, if a cellular UE is scheduled on the same physical resource block (PRB) as a UE-UE link within the cell, it is possible to adjust the beam pattern of both links to achieve maximum orthogonality between different transmissions while still preserving the main energy to their respective receiver. Joint power control can be a further step to mitigate interference resulted from nonideal orthogonality.

However, employing these interference mitigation tools in a fully centralized manner necessitates considerable signaling exchanges between UE-UE pair and eNB, which might include feedbacks of channel quality indicators(CQI) and precoding matrix indicators(PMI), resource grant, power control, synchronization, NACK, etc. The problem of signaling overhead is acute rather in the P2P case as the P2P usage scenario often concerns heavy multimedia data transfer. In plus, in some P2P usage scenario, the deployment can be quite dense. A typical example is in hotspot area such as sports stadium or concert hall where an audience having the same interests might want to share highlights, replays, pictures and video clips among them. P2P configuration is envisaged to help offloading cellular networks in this scenario, however if each pair of P2P UEs in such a dense zone is jointly and dynamically scheduled by the eNB, the signaling overhead can be tremendous. It's crucial to find a solution of coordinated scheduling with modest overhead. At least two approaches can be taken to reduce overhead in the dense deployment scenario of P2P communication mentioned above.

Firstly, assuming that the service type and user buffer state are known at eNBs, it's possible to predict the P2P traffic and schedule the P2P communication in a semi-persistent way. It means, instead of single opportunities, a transmission pattern (in both dimension of time and frequency) is defined for the localized P2P data transfer. This might significantly reduce scheduling assignment overhead. We also propose that in usage scenarios where more than two nearby UEs desiring to communicate among themselves, instead of scheduling these P2P users pair by pair, eNBs treat the group of local P2P users as a whole. eNBs only convey signaling with one UE in this P2P group which will function as a super peer (a sub-coordinator). The super peer manages the internal ad-hoc network to meet the QoS of each subordinate UE. This two-hierarchy coordination might further reduce the overhead particularly for a dense deployment of P2P communication.

III. PARTLY CENTRALIZED SCHEDULING ALGORITHME

In this section, we look deeper into the centralized scheduling method in the dense deployment scenario of P2P communication. In order to limit the signalling overhead, we assume that the two-hierarchy coordination structure and semi-persistent scheduling for P2P communication proposed in the previous section are applied. We detail how an eNB coordinator schedules the cellular UEs in the presence of semi-persistent scheduled local P2P networks, with the purpose of mitigating interference, and increasing the aggregate spectral efficiency. The eNB scheduler also takes into consideration fairness among the cellular UEs. We omit the part how the sub-coordinator UE manage the internal P2P communication in our initial study and only concentrate on the eNB scheduler.

We propose an interference-coordinated scheduling algorithm in eNB which dynamically chooses the cellular UEs to share the same resources with P2P users. By taking advantages of multi-user diversity in cellular networks, it's possible to achieve spatial selectivity within a cell. A user selection algorithm can be resumed as follows:

At one TTI,
For each PRB:
Initialize $S = UE_0, T(S) = T(UE_0)$.
$\hat{k} = \arg\max_{k=1,\dots,K} U_k$
If $T(UE_0 \cup UE_{\hat{k}}) > T(S)$, *update* $S = UE_0 \cup UE_{\hat{k}}$;
else exit.

UE_0 denotes the receiver in a P2P link. K is the total sum of downlink UEs and U the maximizing objective. $T(S)$ denotes the sum rate in one PRB which is allocated to the set of UEs S. The instantaneous rate in one PRB is predicted from receiver SINR by using MIESM (Mutual Information Effective SNR Mapping algorithm) [7, 8] with LTE AMC (Adaptive Modulation and Coding) integrated, and the SINR is evaluated assuming that CSI of the P2P link, as well as the interference channel state, can be available at eNB. At one TTI, for each PRB used by P2P transmission, the user selection algorithm aims at finding one downlink UE for frequency share according to an optimization criterion, and the overall throughput is recalculated taking into consideration interference introduced by frequency reuse. The frequency reuse is only allowed when it increases the total throughput in this PRB.

The optimization criterion can be proportional fair (PF), Maximum C/I (MCI), etc. We propose a modified PF criterion:

$$\hat{k} = \arg\max_{k=1,\dots,K} \frac{T(UE_0 \cup UE_k)}{\bar{r}_k(t)}$$

As it is well known, the conventional PF criterion schedules a user when its instantaneous channel quality is high relative to its own average channel condition over time. For a PRB already occupied by P2P users, the modified PF criterion schedules a downlink UE when total sum rate in this PRB is high relative to its own average rate.

At TTI t, $\bar{r}_k(t)$ is recursively computed by

$$\bar{r}_k(t) = \left(1 - \frac{1}{t_c}\right)\bar{r}_k(t-1) + \frac{1}{t_c} r_k(t)$$

where t_c is the low-pass filter window length over which fairness is imposed and $r_k(t)$ is the instantaneous throughput of user k at TTI t accumulated throughout all the PRBs

$$r_k(t) = \sum_{m=1}^{M} T_m(UE_k)\chi_{km}$$

where χ_{km} indicates whether PRB m is allocated to user k or not, with $\chi_{km} \in \{0,1\}$.

Finally, for PRBs that are not occupied by the P2P communications, a conventional PF criterion is used.

For PRBs already occupied by P2P link, we are more interested in finding downlink UEs which can achieve higher frequency reuse gain than others. While for the rest of available PRBs, we try to allocate them in a way that all the active downlink UEs are served quite fairly. This can be achieved by imposing a large time window t_c when scheduling frequency reused PRBs, and a small time window when scheduling other PRBs.

IV. NUMERICAL RESULTS

The simulation layout is constrained within one sector of a three-sector LTE hexagonal macro cell. NLOS paths are assumed for both P2P and cellular channels. The WINNER channel model [9] is applied. We assume that P2P communication applies the same access technique as LTE DL, namely OFDMA, and operates in the same FDD DL spectrum. In order to examine performance of interference coordinated scheduler in eNB, the internal P2P network is simplified. In our simulation, we assume only one group of P2P exists within the simulating sector. Three P2P receivers exist in this P2P group and are scheduled by the sub-coordinator simultaneously. Each occupies an even portion of bandwidth allocated semi-persistently by the eNB. Other ten active DL UEs are dropped randomly onto the same sector. Out of a total 5MHz DL bandwidth, a sub-band of 1.4MHz is allocated semi-persistently (throughout whole simulation time) to the local P2P group. Other simulation parameters are listed below in Table I.

TABLE I. SIMULATION PARAMETERS

System Parameters	
Center Frequency	2GHz
DL Bandwidth	5MHz (25PRBs)
Inter-site distance	500m
Thermal noise PSD	-174dBm/Hz
Antenna Parameters	
Max Tx Power	eNB: 43dBm, UE: 24dBm
Antenna polarization	eNB: 4Tx cross polarization UE: 2Tx linear polarization
Maximum antenna gain	eNB: 17dBi, UE: 0dBi
Antenna height	eNB: 25m, UE: 1.5m
Noise Figure	7dB
Others	
Number of drops	50
Simulation duration	1s (1000TTIs) per drop
User velocity	3km/h
P2P to eNB distance	200m
P2P distance	15m
Traffic model	Full buffer

We assume perfect CSIT, and apply one layer SVD precoding to each link. The inter-cell interference is modelled as background noise, with a constant power spectral density (PSD) value of -130dBm/Hz. The post receiver SINR is calculated on subcarrier base after a conventional MMSE receiver. The mutual information effective SINR mapping (MIESM) is conducted to approximate the resultant block error rate (BLER). Therefore the throughput is calculated from

$$\tau = b_{\mathrm{MCS}}(1 - BLER)$$

where b_{MCS} is expressed in bps/Hz, indicated by the underlying MCS. The highest supported data rate in the simulation is 4.5 bps/Hz, corresponding to 64-QAM with a 3/4 code rate.

The scheduling method proposed in section III is compared to exclusive resource allocation where the spectrum allocated to P2P networks is not reused by cellular UEs within the same sector. For comparison, the reference of pure cellular networks is also added where all the users are scheduled in DL with a proportional fairness algorithm.

When scheduling cellular UEs in the spectrum which is already semi-persistently allocated to P2P networks, a large time window of 100 is used. While for the rest of the spectrum available in the system, a small time window of 2 is used. The same time window of 2 is applied when scheduling cellular users with exclusive resource allocation method and in pure cellular networks as well.

In Table II, the aggregate cell throughput is compared. The frequency reuse on the 1.4MHz sub-band generates 11.4% gain comparing to the hybrid scheme without frequency reuse. The gain is much higher (29%) comparing to pure cellular networks.

In the same table, the throughput of P2P indicates that in hybrid networks, interference resulted from frequency reuse within a sector doesn't degrade the P2P channel. The P2P throughput with our proposed frequency reuse scheduling remains almost the same as that in non-reuse case.

TABLE II. COMPARISON OF HYBRID AND PURE CELLULAR NETWORKS

Measurements	***Pure Cellular***	***Hybrid Non-reuse***	***Hybrid reuse***
Aggregate throughput (Mbps)	13.38	15.51	17.27
P2P throughput (Mbps)	/	4.85	4.85

The cumulative distribution function (CDF) of average cellular user throughput is plotted in Figure 2. A zoom of 5%-tile cell edge user throughput is plotted in Figure 3. The throughput of hybrid networks is much higher than that of pure cellular networks at the 50% CDF level. It's mainly due to the better usage of spectrum enabled by shorter range direct UE-UE communication. Note that in this simulation the communication distance is reduced from 200m in DL mode to 15m in P2P mode. The in-band frequency reuse scheme achieves the best usage of spectrum. Even the cell edge users in in-band frequency reuse scheme are not degraded by intra-cell interferences. One of the reasons is that a large time window is employed for fairness criteria on the reused resources which reduce the chance that a cell-edge cellular UE be scheduled for frequency reuse. It can be shown that the in-band frequency reuse interference is well controlled by the proposed coordinated scheduling and the user experience is greatly improved by introducing P2P hybrid networks.

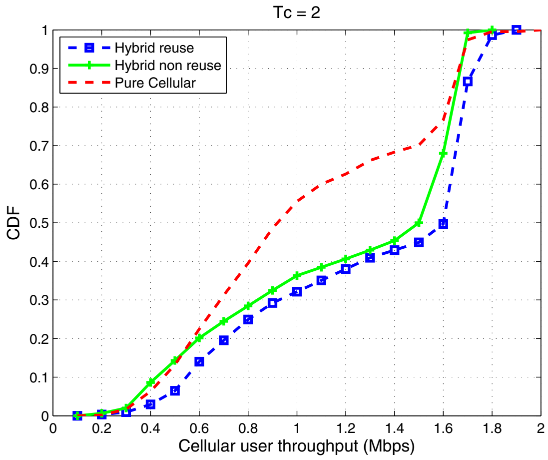

Figure 2. CDF of average per user throughput

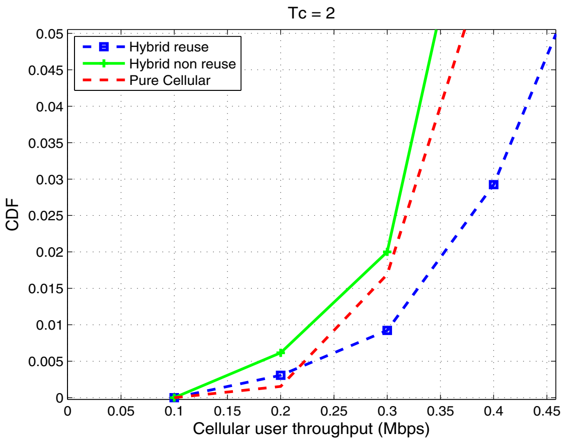

Figure 3. CDF of average cell-edge user throughput

In this two-hierarchy coordination architecture, it's possible to localize most of the signaling required by P2P communications. Signaling for P2P link establishment, synchronization, resource allocation and HARQ, etc. can be restricted internally between the P2P user and sub-coordinator. Therefore the overall overhead can be significantly reduced.

In our simulation, in order to facilitate the examination of interference budget, a fixed transmission pattern is defined for P2P transmission. However in practice, depending on traffic loads in the cell and P2P service types, this transmission pattern should be adjusted by the central scheduling algorithm.

Furthermore, to make a realistic full system level simulation, all users in a cell should be simulated equally without presuming the existence of P2P links. P2P links should be decided using scheduling algorithms. To this end, a proper traffic model should be established firstly, with packet buffers bearing information of both source and destination user IDs, and of QoS requirements.

V. CONCLUSION

In this article, coordination for in-band ad-hoc transmission underlaying cellular networks is analyzed in both stages of session setup and data transfer. Two-hierarchy coordination with moderate overhead is proposed for dense P2P deployments. An in-band frequency reuse scheduling algorithm in eNB is presented which dynamically chooses the cellular UEs to share the same resources with P2P users. The system level simulation results show that the proposed interference coordinated scheduling effectively mitigates the intra-cell frequency reuse interference and makes a better usage of the spectrum. The initial evaluation demonstrates a considerable improvement on the aggregate cell throughput as well as on the average user experience by introducing in-band direct P2P communications into cellular networks.

For the future study, several improvements can be made. Power control and advanced MIMO techniques are promising candidates for achieving higher performance gain in the frequency reuse scheme. The semi-persistent resource allocation should be included as a dynamic element in the central scheduling in eNB. Finally, a more practical non-full buffer traffic model should be applied and a QoS-aware scheduling method is worth an investigation.

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