Cellular Controlled Short-Range Communication for Cooperative P2P Networking

Frank H.P. Fitzek[1], Marcos Katz[2] and Qi Zhang[3]

Aalborg University[1], Denmark, VTT, Finland[2], Technical University of Denmark[3]

Abstract— **This article advocates a novel communication architecture and associated collaborative framework for future wireless communication systems. In contrast to the dominating cellular architecture and the upcoming peer-to-peer architecture, the new form envisions a cellular controlled short-range communication network among cooperating mobile and wireless terminals. The novel architecture together with several possible cooperative strategies will bring clear benefits for the network and service providers, terminal manufacturers as well as the end users.**

***Index Terms*— cooperation, wireless networks, cellular, short-range, composite networks.**

I. Introduction

Currently the cellular communication scene is dominated by the transition from the second (2G) to the third generation (3G). Some of the key problems of those communication systems include the limited achievable data rate over the air interface and the lack of new and appealing services motivating the customers to shift their 2G mobile devices to 3G ones. While designing the architecture of future wireless networks, i.e., 4G, another challenge becomes evident: the ever increasing power consumption of the mobile device. By cramming terminals with a large number of "placebo" functionalities and capabilities like advanced imaging features (camera, high-definition display, etc.) as well as versatile and high-performance wireless connectivity including short-range communication (Bluetooth, WLAN, etc.), and higher data rates over the cellular interface, manufacturers face a serious problem: A dramatic and critical increase of power consumption of the mobile device. This has two major impacts: first, the absolute power consumption could make active cooling of the mobile device necessary, and secondly, the active usage time decreases, as the developments in battery capacity and efficiency cannot cope with the steep power consumption increase. The operative time of mobile devices has been identified as the number one criteria to purchase a mobile device. Thus, a solution has to be found aiming at decoupling the problem of increasingly more complex mobile devices on one hand, and the need for supporting higher data rates (which is the enabler for new services).

In this contribution we advocate a novel paradigm which tightly and dynamically combines centralized networks (e.g., cellular) with distributed networks (e.g., ad hoc, short-range, peer-to-peer).

II. Motivation for the Proposed Novel Architecture and Associated Cooperative Framework

Omnipresent cellular communication systems are characterized by the communication between a base station and mobile terminals as given in Figure 1. In [1] a novel communication architecture referred to as micro cooperative networking was introduced. The idea is to enable direct communication between mobile devices using the short-range communication technology available also onboard, while the cellular communication link is still enabled, as illustrated in Figure 2.

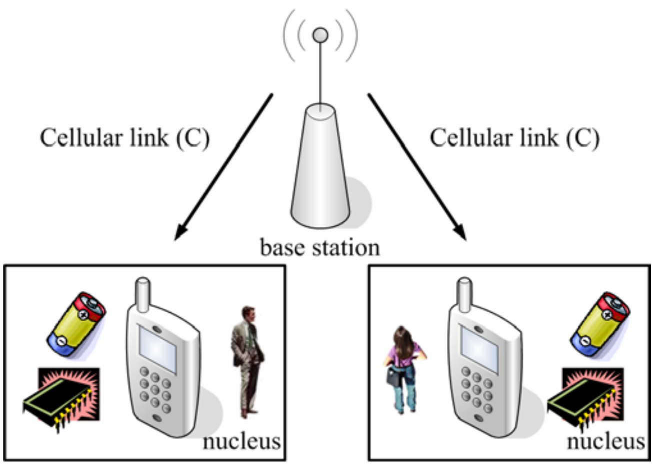

Figure 1: Conventional Cellular Communication Architecture.

Mobile devices are able to create cooperative clusters with neighboring devices in their proximity. While the distance between the base station and the mobile device can typically be of up to several kilometers, the short-range link is usually limited to several tens of meters at the most. Each terminal is then contributing to the cooperative cluster with its cellular link, energy of its battery, and some of its processing power. The grouped members can then be used as virtual entities in a cooperative manner aiming at overcoming the above described problems. This hybrid network combining a centralized and distributed architecture is referred to as composite *network*. The cellular link has a key role with the proposed architecture as it is needed as the service entry point and to perform administrative tasks such as authentication, billing, management, etc.

Therefore the architecture is referred to as *cellular controlled short-range communications* (CCSRC). Note that combination of cellular and ad hoc networks have been proposed before, see for instance [3] and [5]. In [5] the architecture was introduced for multi player architectures, where the cellular link was used for game updates such as maps and high scores and the local links where used for the actual gaming. It has been shown in that paper that the cellular network operator can benefit from such an architecture by an increased dollar per bit ratio on the cellular link.

However, the considered solutions approach such a system from a more rather static standpoint, targeting usually range extension and data throughput enhancements by using multi-hop techniques between the two networks. The here proposed architecture and associated cooperative framework exploit dynamically cooperation in two domains, namely a) *inter-network cooperation*, encompassing the collaborative interaction between the centralized and distributed networks, and b) *intra-network cooperation*, exploiting the interaction taking place within the distributed short-range network (i.e., cluster). Such collaborative framework constitutes the key underlying principle associated with the composite architecture. The cooperation is described as a non altruistic form of collaboration in which each terminal joins the cooperative group as long as it gains instantaneously. The cooperative behavior is based on egoistic reasoning.

The fundamental idea behind the considered network and associated collaborative framework is exploiting the resulting synergy of having a component networks with highly complementary characteristics, combining features such as, licensed and license-exempt spectrum usage as well as high power / wide area / low data rate together with low power / short-range and high data rate. Moreover, the considered strategy bring the two main component networks of current and future wireless communication systems in a closer and amicable relationship, rather than regarding them just a coexistent networks or even competing ones in the worst case. This brings, in addition to the technical advantages, a universal convergence platform as well as a politically attractive solution embracing the two prevailing models of wireless communications. Note that in principle any type and air interface technology of distributed short-range network can be employed.

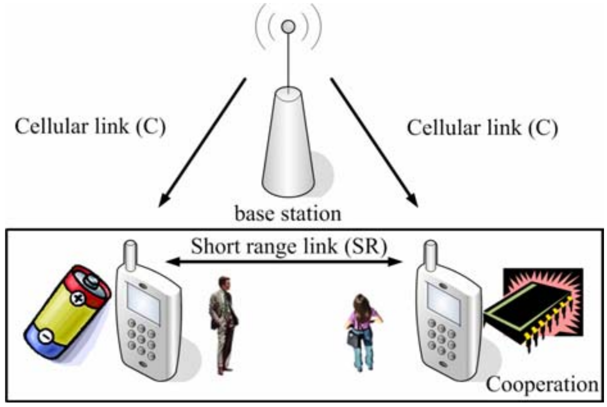

Figure 2: Cellular Controlled Short-Range Communication Architecture.

The benefits of the proposed composite architecture and associated collaborative framework are manifold:

- **Overcoming the limited cellular capacity**: For both, unicast and multicast services, the cooperating mobile devices bundle their cellular air interfaces to get a bigger pipe for the cooperative cluster. For multicast services such as video streaming or file downloading the benefit is obvious. In this case the cooperative devices receive partially the original stream and collaboratively merge it later over the short-range communication links. The CCSRC is also beneficial for unicast services as well. As a simple example we refer to web browsing. The traffic model is characterized by a strict on-off model. If one out of the cooperative cluster requests a web page, the content is conveyed from the network towards the target mobile device using the diversity of the cooperating cluster. We refer only to a limited set of examples but refer the interested reader to our follow up works [1].

- **Power Consumption**: In [1] we have discussed the power saving capabilities of the CCSRC architecture. Comparing the overall power expenditure of a non cooperative scenario versus the cooperative scenario, in many cases cooperation does paying off.

- **Service**: A current problem of service and network providers is that novel services are high priced and therefore only a limited number of customers can afford them. With the CCSRC architecture, the cost of a cooperative service can be lower than that for a non cooperative one. E.g., while a non cooperative approach pays 100% of the service, three cooperative customers could be paying considerably less, e.g., 50% each. In this case both, the cooperative customers and the network/service providers gain. Being the aforementioned example only an initial guess, it is clear that billing methods and incentives to encourage cooperation have to be developed to get attractive business models for the network/service provider and to stimulate and motivate cooperative networking among users.

- **Security**: Due to the cellular link diversity, new schemes for security can be developed. As the cooperating entities have a predefined or reliable knowledge about the other cluster members, these entities can be seen as trustable relays. The architecture also lend itself naturally to the implementation of advanced highly secure schemes where information is *network multiplexed*, that is secured information is conveniently spread over the cellular and distributed network and combined at the target destination. Security in terms of content ownership are addressed in [4] for P2P networks.

- **Spectrum:** The synergetic use of both networks has the potential to enhance the spectral efficiency. This can be easily illustrated by considering an example of multicast transmission to the members of a cooperative cluster. A packet (transmitted by the base station) which fails to be received by a given member (die to unfavorable channel conditions) needs not to be retransmitted by the base station but locally by another member of the cluster, without consuming licensed spectrum. This form of collaborative diversity has a positive impact on spectrum usage.

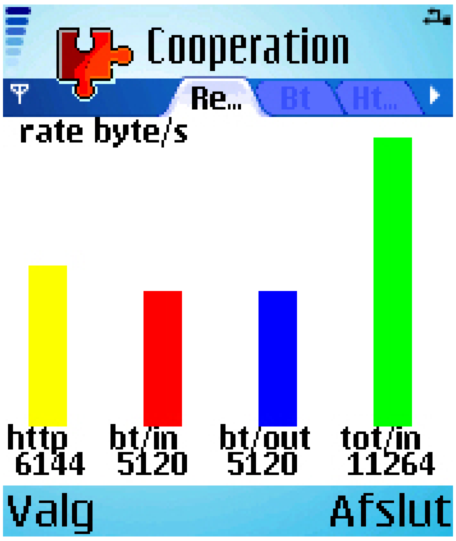

Figure 3: Terminal screenshot (Nokia N70) for the two cooperating entities case. The data rate over the cellular link (yellow), the short-range link (red/in and blue/out) and the virtual link (green) is given.

III. Realization of the Cellular controlled Short-Range communication Architecture

There are two main directions to implement the envisioned architecture, namely through a *multi modality* or a *common air interface* approach. The multi modality approach can be realized already with 2G or 3G mobile devices which are equipped with cellular and short-range communication capabilities. One example employing today's technology could be a terminal with dual GPRS and Bluetooth air interfaces. A first implementation of this scenario has been carried out at Aalborg University on the Symbian OS platform using commercially available terminals (Nokia N70). Two cooperating phones, as those shown in Figure 2, agree on splitting a file to download and start to receive it over the GPRS link. Simultaneously the received data is exchanged over the short-range link. Measurements have shown, that the downloading time is reduced down to 50% and energy savings of 45% where achieved for only two cooperating mobile devices. That the energy consumption is nearly cut into half by one cooperating terminal is quite promising. The values may change for different services. Video services require more power for the display and for the decoding process. We note that the cooperative approach will get the benefit mostly from the RF/BB part.

Figure 3 depicts a screenshot of one of the cooperating terminals where the contributions of the cellular, short-range and virtual (cooperatively combined) links are displayed. Note that additional gain can be achieved if more devices collaboratively interact.

The second direction focuses on a new air interface design. Indeed, while the multi modality concept is based on two orthogonal spectrums, the common air interface is focusing on flexible splitting the spectrum for cellular and short-range communications. Such adaptive splitting can be done either in the time or frequency domain (or in both). The later fits naturally better in future wireless networks (4G) networks where OFDM has been identified as the main access technology. As the common air interface requires flexibility in the air interface, the software defined radio (SDR) concept is applicable. It has been shown that software controlled radio (SCR) is more beneficial for pure cellular communication systems as flexibility is not needed. CCSRC requires flexibility as well and therefore SDR appears as the most promising solution.

In Figure 4 a possible flexible air interface based on OFDMA is illustrated. The given spectrum is divided into a 4:1 ratio for the cellular and short-range links, respectively. The cellular service is provided into four non overlapping sub-streams (frequency bocks) D1 to D4. The upper part of the spectrum (20%), on the right hand side of Figure 4, is reserved for cooperative exchange of the sub-streams. Within the short-range frequency spectrum the achievable data rate (modulation and coding) is assumed to be four times larger than on the cellular part (in general this value could much larger, as these are in fact short-range links). A non cooperative approach would receive on all four sub-streams to achieve the full service utilizing 80% of the spectrum. However, the cooperative approach, using the same service, would receive one of the four cellular sub-streams and contribute/listen on the short-range communication using 40% of the spectrum. In case of OFDMA the FFT size for the non cooperative case is twice of the cooperative one. This is under the assumption that we have a flexible air interface that can be tuned to and limited to the necessary sub-streams. The complexity of the mobile device is partially affected by the FFT size with N(log N) and the benefit by a cooperative approach becomes obvious.

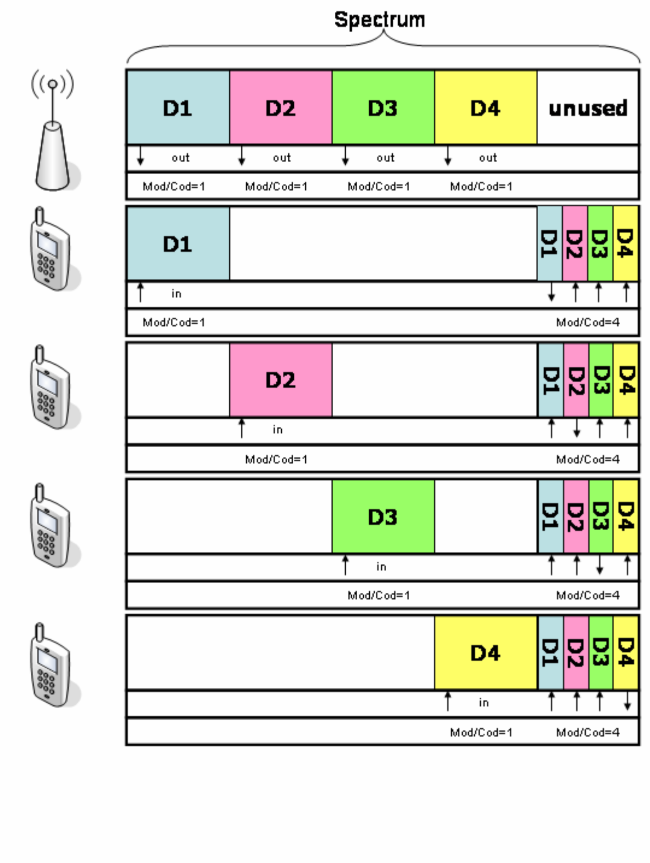

Figure 4: CCSRC with OFDMA.

IV. Short-Range Communication as the Main Driving Force for Cooperative Networking

The short-range communication capability is a must for functional cooperative networking in a CCSCR. Furthermore, the short-range technology dependent system parameters determine how large the benefit of CCSRC can be. These parameters include the data rate of the short-range technology, the power consumption (sending, receiving, idle), and medium access control (MAC) operations. While the data rate and the energy values have a clear impact on the energy per bit ratio (EpBR), the impact of the MAC may not be necessarily obvious. Therefore, as an example we refer to wireless local area network (WLAN) and Bluetooth as representative candidates for distributed and centralized short-range communication approaches, respectively. Certainly, wide-area cellular networks could also be considered in the example. While WLAN supports the mobile device providing the cellular information received over the WLAN in a multicast fashion, Bluetooth does not. In a Bluetooth-based communication network, the master terminal is able to control the communication of up to seven active slaves and some more inactive slaves. No direct communication between slaves is possible and therefore the transparent energy per bit ratio (TEpBR), defined as the overall energy needed to convey information from a particular slave to another one (via the base station), is larger than the EpBR. To illustrate this concept, we consider the WLAN scenario, with *J* cooperative devices. In such as scenario *J* multicast packets are exchanged among the mobile devices. Each mobile device sends one packet to the cooperating device and expects *J*-1 packets to receive as given in Table 1.

If one wants to get a better insight on the number of packets sent over a Bluetooth enabled cooperative cluster, the calculation becomes a slightly more complex: First the master can multicast its own packet towards the *J*-1 mobile slave devices. The *J*-1 mobile slave devices cannot multicast their packets directly to the neighboring slaves and need to relay them over the master. This ends up in an overall number of packets sent equal to 2*J*-1. It is important to note, as given in Table 1, that the master is more active than the individual slaves. While the power consumption of the slave is equal to a cooperating mobile device in the WLAN scenario, the master takes all the burden has he is sending *J* times more packets than the slaves. Because of this a round robin of the master role would be fair. In this case the mean value of send packets is 2-1/*J*. For large values of *J*, we can say that we need the double number of packets to exchange, which also doubles the TEpBR values in contrast to the EpBR. As one conclusion on the designing principles for future short-range wireless networks, we can highlight the importance of the three key factors, data rate, power values, and the used MAC concept.

Table 1: Number of packet exchanges for the WLAN and the Bluetooth case (master and slave separated).

	Sending		Receiving	
WLAN	1		J-1	
BT	Master	Slave	Master	Slave
individual	*J*	1	*J*-1	*J*-1[1]
mean	2-1/*J*		*J*-1	

V. MAC Requirements for CCSCR

A lesson learned from last section is that the MAC should support direct communication between cooperating entities in a point-to-multipoint fashion. The reason is to avoid relaying through a central entity as it would happen in the Bluetooth communication case. Furthermore, to minimize the idle time as well as to reduce collision times, the channel should be slotted in time or frequency. This is not viable in IEEE based WLAN systems. For the power saving it is crucial to be able to switch on and off the RF/baseband chain in time domain or to dynamically enable/disable frequency bands reducing the complexity, a feature that can be found in DVB-H technology.

VI. Conclusion:

In this paper we have proposed and discussed a composite architecture and related cooperative framework with high potential to tackle several crucial impairments of current and future wireless networks like energy (and power) efficiency, spectral efficiency, system capacity, QoS, security, etc. In the considered approach a centralized network (cellular) dynamically and collaboratively interact with a local distributed network connected over short-range links (ad hoc, peer-to-peer) aiming at achieving a better use

[1] The number *J*-1 is correct if slaves are not listening to the relaying of their own packets. It may be beneficial to receive all *J* relaying packets, to avoid overwhelming signaling. This is a system design matter and needs to be investigated in the future. For large number of *J* this is a minor problem.

of resources (mostly energy and spectrum), enhancing quality of service and system performance.

It is believed that the presented concepts and scenarios open up a fertile and multidisciplinary field for further exploration. The envisioned concept has the possibility to unify the cellular and P2P network ideas. Currently the cellular network operators scare the new P2P network concepts as they cannot control it. But the proposed architecture will enable the network operators to break new ground for new business cases.

The paper illustrates the key role of short-range communications for cooperative networks. It is essential that the designing rules for the MAC should support the cooperative networking.

REFERENCES

[1] F.H.P. Fitzek and M. Katz. Cooperation in Wireless Networks: Principles and Applications - Real Egoistic Behavior is to Cooperate!, 2006. Springer.

[2] Aalborg University, Cooperative Mobile Phones, http://kom.aau.dk/project/mobilephone/index.php?section=28.

[3] H. Hsieh and R. Sivakumar, "On Using Peer-to-Peer Communications in Cellular Wireless Data Networks", IEEE Tans. On Mobile Computing, Vol. 3, No. 1, pp., 57-72, Jan.-Mar. 2004.

[4] Michael Stini, Martin Mauve, Frank H.P. Fitzek, Digital Ownership: From Content Consumers to Owners and Traders, IEEE MultiMedia, vol. 13, no. 4, pp. 1, 4-6, Oct-Dec, 2006.

[5] F.H.P. Fitzek and G. Schulte and M. Reisslein. System Architecture for Billing of Multi-Player Games in a Wireless Environment using GSM/UMTS and WLAN Services. 2002. in Proceedings of the First Workshop on Network and System Support for Games (NetGames 2002), pages 58-64. Braunschweig, Germany.

Frank H. P. Fitzek is an Associate Professor in the Department of Communication Technology, University of Aalborg, Denmark heading the Future Vision group. He received his diploma (Dipl.-Ing.) degree in electrical engineering from the University of Technology - Rheinisch-Westfälische Technische Hochschule (RWTH) - Aachen, Germany, in 1997 and his Ph.D. (Dr.-Ing.) in Electrical Engineering from the Technical University Berlin, Germany in 2002 for quality of service support in wireless CDMA networks. As a visiting student at the Arizona State University he conducted research in the field of video services over wireless networks. He co-founded the start-up company acticom GmbH in Berlin in 1999. In 2002 he was Adjunct Professor at the University of Ferrara, Italy giving lectures on wireless communications and conducting research on multi-hop networks. In 2005 he won the YRP award for the work on MIMO MDC and in 2005 he received the Young Elite Researcher Award of Denmark. His current research interests are in the areas of 4G wireless communication networks, cross layer protocol design and cooperative networking.

Marcos Katz received the B.S. degree in Electrical Engineering from Universidad Nacional de Tucumán, Argentina in 1987, and the M.S. and Ph.D. degrees in Electrical Engineering from University of Oulu, Finland, in 1995 and 2002, respectively. He worked as a Research Engineer at Nokia Telecommunications from 1987 to 1995, designing analog circuits for high-speed PDH/SDH line interfaces. From 1995 to 2001 he was a Senior Research Engineer at Nokia Networks, Finland, where he developed multiple antenna techniques for several TDMA and CDMA research projects. In 2001-2002 he was a Research Scientist at the Centre for Wireless Communications, University of Oulu, Finland, where he concentrated on synchronization problems of CDMA networks. In years 2003-1005 Dr. Katz was the Principal Engineer at Samsung Electronics, Advanced Research Lab., Telecommunications R&D Center, Suwon, Korea. From 2006 his works as a Chief Research Scientist at VTT, the Technical Research Centre of Finland. His current research interests include synchronization, multi-antenna techniques, cooperative and cognitive techniques, as well as optical communications, all aiming at future 4G wireless communication systems. From the beginning of 2006 he is serving as the vice-chair of Working Group 5 (short-range communications) for the Wireless World Research Forum (WWRF).

Qi Zhang is a Ph.D student working on her Ph.D. project (Cooperative Communication in Wireless Network) at COM department in Technical University of Denmark. She received her B.Sc. degree in Electronic Engineering from Nanjing University Posts & Telecommunications in China in 2002, and M.Sc. degree in Telecommunications from Technical University of Denmark in 2005. She worked as lecturer in Jiangsu Fujistu Company in China in 2003. She also worked in Dansk Telecom in Denmark from 2004 to 2005. Her current research interests are Cooperative Communication, Network optimization, QoS of real time service in wireless network, Traffic analysis and control, 4G system architecture design.