Device-Centric Wireless Networks for 5G

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Abstract- **Cellular networks face significant capacity and energy challenges as a result of the continuous and exponential growth of cellular data traffic. These growth levels are predicted to be maintained in the years to come, and 5G networks will be required to efficiently support them. One of the potential 5G key enabling technologies to address these challenges will be device-centric wireless networks. Device-centric wireless networks represent a paradigm-shift in the design of future cellular technologies as they transform mobile devices into prosumers of wireless connectivity. In this context, this paper introduces device-centric wireless networks, and illustrates their potential to improve energy efficiency, quality of service and capacity compared to traditional single-hop cellular communications. The paper focuses on multi-hop cellular networks, and on the opportunities that the integration of opportunistic networking and device-centric wireless networks offer to achieve the 5G goals.**

I. INTRODUCTION

Future 5G networks are being designed with the objective to handle the exponential growth in data traffic, and support very large numbers of connected devices with different requirements and characteristics. Current estimates foresee that the mobile traffic will increase by a factor of 500 to 1000 due to 10 to 100 times more connected devices in the next decade [1]. In addition, 5G networks will be required to increase end-user data rates (10 to 100 times), reduce end-to-end latency (in the order of 1ms) and more efficiently support varying QoS (Quality of Service) and QoE (Quality of Experience) requirements. All this should be achieved while saving up to 90% of energy per provided service [1]. Addressing these challenges will require a paradigm-shift in the design of future 5G networks. Current technologies being investigated include, among others, mmWave, massive-MIMO (Multiple Input Multiple Output) and (ultra) dense deployment of small cells. Device-centric wireless solutions are also receiving significant attention due to the increasing computing, storage and connectivity capacity of mobile devices. Device-centric wireless networks advocate for the need to explore and evolve from current cell-centric architectures to device-centric one. The device-centric perspective has been lately fuelled by the identified benefits from Device-to-Device (D2D) communications that facilitate new value added services (including proximity based services), support public safety applications, help offload cellular traffic from the BSs, and increase the spatial frequency reuse and capacity [2]-[3].

Device-centric wireless solutions include D2D and Multi-hop Cellular Networks (MCNs). MCNs utilize mobile relays and D2D communications to substitute long distance, and generally Non-Line Of Sight (NLOS), cellular links by multiple hops, which reduces the pathloss and increases the link budget compared to long distance single-hop cellular links. Device-centric wireless solutions offer then unique capabilities to overcome the fundamental communications and radio propagation limits of traditional cell-centric architectures. The development of device-centric wireless networks is though not free of challenges, for example in terms of the need for flexible device-centric architectures, mode selection schemes in multi-band and multi-RAT (Radio Access Technologies) scenarios, efficient and lightweight discovery and peer management processes, and security, among others.

Device-centric wireless networks evolve devices from mere data sinks to more active nodes that participate in the network management and operation through a carefully designed cooperation and coordination with the cellular infrastructure. Smart mobile devices will provide wireless connectivity to other mobile devices (using multi-hop communications) and will hence act as a bridge between the cellular infrastructure and other devices (in case of MCN), or between devices (in case of D2D) for more efficient transmissions. Device-centric wireless networks, whether D2D or MCN, will transform mobile devices into prosumers of wireless connectivity in an underlay network that if efficiently coordinated with the cellular network has the potential for significant capacity, energy-efficiency and QoS benefits. This paper presents research activities that contribute towards the development of viable and efficient device-centric wireless networks, and demonstrate the potential of device-centric wireless solutions to address the 5G challenges. In particular, this paper focuses on MCNs, and first presents experimental results that demonstrate how MCNs using mobile relays can overcome the limitations of traditional cell-centric networks. The paper also presents a novel context-aware scheme that integrates opportunistic networking and device-centric wireless communications to improve the energy efficiency.

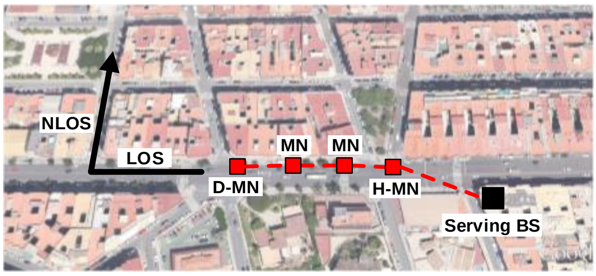
II. EXPERIMENTAL MCNS

Previous analytical and simulation-based studies have proved the benefits that MCNs using mobile relays can provide in terms of capacity, cell coverage, network scalability, infrastructure deployment cost, power consumption and energy efficiency. However, there was yet the need to experimentally demonstrate the benefits of device-centric MCNs technologies. In this context, this section summarizes activities carried out at UWICORE to validate and quantify the benefits that device-centric MCNs can provide over traditional cell-centric systems through field tests, and the conditions under which such benefits can be obtained [4]. To this aim, UWICORE has implemented and designed a unique MCN hardware testbed, referred to as mHOP, together with the necessary software tools to monitor the operation, and quantify the QoS and benefits of device-centric MCNs with respect to traditional cellular communications. The implemented mHOP platform focuses on downlink transmissions, and includes MCN and conventional single-hop cellular links to communicate a destination Mobile Node (MN) with the Base Station (BS). In the case of the MCN connection, the BS transmits using HSDPA cellular technologies to a hybrid MN[1], and this node forwards the information to the destination MN through a set of intermediate MNs. Intermediate MNs link the destination and hybrid MNs by means of D2D communications using IEEE802.11g at 2.4GHz. It is important noting that 3GPP TR22.803 considers 802.11 as well as cellular technologies (i.e. LTE-Direct) for D2D communications.

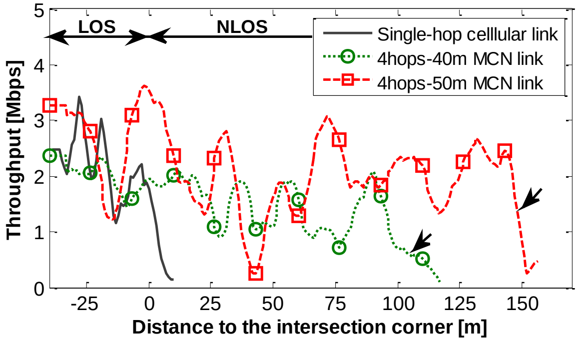
The cellular links are implemented using a Nokia 6720c handset that incorporates the Nemo Handy application, which provides the terminal with a powerful radio monitoring capability offering a valuable set of Key Performance Indicators (KPIs) such as throughput, Block Error Ratio (BLER), or Received Signal Strength Indication (RSSI). The mobile relay nodes are currently implemented in conventional laptops under Linux due to the configuration possibilities and availability of open tools/libraries. The mobile relaying nodes have been equipped with an external IEEE 802.11 wireless ExpressCard to carry out the D2D transmissions, and they also incorporate an IEEE 802.11 packet sniffer software developed at UWICORE to monitor the quality of D2D links using the ExpressCard and the built-in wireless interfaces. Both cellular and D2D connections provide spatial and time synchronized measurement results through the use of external GPS devices [4].

The field trials presented in this paper were conducted in the city of Elche using Orange's live cellular networks. Fig. 1 illustrates an example of the capacity of device-centric MCN technologies to improve the QoS compared to traditional single-hop cellular communications. During the field tests, a destination MN (D-MN) moves away from the serving BS following the path illustrated in Fig. 1.a. This path includes an intersection corner that reproduces the traditional signal attenuation experienced when passing from LOS to NLOS conditions. The D-MN can establish the connection to the BS either through a traditional single-hop cellular connection or through a MCN one. In the latter case, D-MN connects to the BS through two mobile relay (MN) nodes and a hybrid MN (H-MN). Tests have been conducted with different distances between mobile nodes: 40 and 50 meters. The field tests consider downlink transmissions of long-size files from the serving BS to the D-MN. When the tests start, mobile nodes walk towards the intersection corner with the D-MN being the first to turn around the corner. As the download continues, the H-MN reaches the corner. The H-MN is locked to the serving BS (using Nemo Handy) to prevent a handover to a neighboring BS when turning around the corner.

Fig. 1.b shows the throughput experienced by a single-hop cellular connection between the serving BS and D-MN. The negative distances represent the distance to the corner under LOS conditions, and the positive ones the NLOS distances after turning the corner. The reported measurements show how the single-hop cellular QoS rapidly decreases after entering NLOS conditions. Fig. 1.b also shows the throughput experienced at the D-MN for the two MCN configurations. The point at which the H-MN reached the corner is marked in Fig. 1.b with the black arrows. The reported results demonstrate that MCNs can improve NLOS QoS performance at the D-MN to levels experienced under LOS conditions with the serving BS. Fig. 1.b also highlights the impact of the MN selection on the MCN performance. The MCN benefits can be extended at larger distances with the increasing separation distance between MNs, but it also results in temporary deeper QoS degradations (see for example the performance with '4hops-50m MCN link' at 40m) when the link between MNs experiences NLOS conditions.



a) Testing environment



b) Field test results

Fig. 1. Experimental demonstration of the capacity of device-centric MCNs to improve QoS levels under NLOS.

Additional field tests were conducted under different operating conditions and locations [4]:

1) Field tests were conducted in the overlaid area between two cells where handovers take place. The field tests showed that MCN technologies can help improve the QoS during a handover. To this aim, the single-hop connection is replaced when the mobile station enters the handover area with an MCN connection. The MCN connection uses a hybrid MN located outside the handover area and with good propagation conditions to the BS. The obtained results showed that the MCN connection is capable of guaranteeing at the destination MN the same quality in the handover area as experienced by the hybrid MN outside the handover area. The conducted tests showed that MCN can improve the throughput experienced in the handover area by on average 60% compared to single-hop cellular communications.

2) The conducted field tests also demonstrated that device-centric MCNs can extend the QoS experienced by users close to the BS to users at large distances to the BS. During the tests, the destination MN was fixed at the cell edge, while the location of the intermediate MNs and the hybrid MN was determined by the MCN configuration. With the increasing number of hops and hop distances, the hybrid MN was located closer to the BS experiencing higher QoS

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[1] LTE was not yet deployed in Elche at the time the tests were conducted.

levels. The experimental results showed that MCNs can provide the destination MN with the same QoS level as experienced by the hybrid MN for all the analyzed MCN configurations.

3) Field tests were also conducted to demonstrate the capacity of MCNs to extend the cell range, which can be particularly beneficial for public safety and areas with poor coverage. In this case, the extended cell range was determined by the distance between the destination MN and the hybrid MN (depending on the number of hops and the distance between intermediate MNs) when the hybrid MN reached the cell boundary. The conducted field tests show that, for example, a MCN link with 3 hops and distances among MNs of 60m can extend the radio coverage by 25%.

4) Additional field tests also demonstrated how device-centric MCN technologies can extend to indoor environments the QoS experienced outdoors under good propagation conditions to the serving BS. The field trials were conducted in a shopping center in the city of Elche. During the tests, the destination MN was first directly connected to an outdoor serving BS with LOS propagation conditions to the entrance of the shopping center. The destination MN is locked to this BS as it enters the center. The obtained results show that using traditional single-hop cellular transmissions, the destination MN rapidly experiences a QoS degradation when entering the shopping center. During the second series of tests, the destination MN is connected to the serving BS through a MCN connection. At the start of the tests, the hybrid MN was located outside the shopping center with LOS conditions to the serving BS. The intermediate and destination MNs were located inside the shopping center. During the tests, all the MNs moved inwards with the test finalizing when the hybrid MN enters the shopping center. The trials demonstrate that with 2 intermediate MNs and a distance among MNs of 75m, the destination MN can extend the output QoS experienced at the entrance of the shopping center 150m inwards.

Field tests were also conducted to experimentally evaluate the energy benefits that can be obtained with device-centric MCNs compared to traditional single-hop cellular communications. These tests were conducted for uplink transmissions since the energy consumed at the BS for downlink transmissions could not be measured. The field tests compared the energy consumed by a single-hop HSUPA cellular connection from a destination MN located inside a building (50 meters to the entrance of the building) to an outdoor serving BS, to that measured when the destination MN is connected to the serving BS using a 2-hop MCN connection. With the 2-hop MCN connection, the destination MN connects to the serving BS through a hybrid MN located at the entrance of the building and experiencing LOS conditions with both the BS and the destination MN. The distance between the destination MN and the hybrid MN is 50 meters. The conducted field tests showed that the single-hop uplink HSUPA cellular transmission required on average a transmission power of 15 dBm and consumed 1.06 µJ/bit; the energy consumption was measured using Nokia's Energy Profiler application. In the case of the 2-hop MCN connection, the cellular transmission from the hybrid MN to the BS required on average a transmission power of -20 dBm and consumed on average 0.23 µJ/bit. The IEEE 802.11 D2D transmission from the MS to the hybrid MN consumed on average 0.29 µJ/bit. For these tests, the IEEE 802.11g transmission between the destination MN and the hybrid MN was conducted using a Nokia N97 handset so that the energy consumption could be measured with the Nokia's Energy Profiler application. In total, the MCN connection only consumed 0.52 µJ/bit, which represents a 50% reduction in the consumed energy compared to the single-hop HSUPA cellular transmission.

III. CONTEXT-AWARE OPPORTUNISTIC DEVICE-CENTRIC WIRELESS NETWORKS

The previous section has experimentally shown that device-centric MCNs can help address the increasing QoS, capacity and energy constraints of traditional cellular systems through the integration of cellular and D2D communications using mobile relays. Device-centric MCNs can also benefit from the adoption of opportunistic networking solutions. Opportunistic schemes exploit the nodes' mobility and the store, carry and forward paradigm to establish communication links when favorable communication conditions are found. Opportunistic schemes can then reduce the overall energy consumption, but can result in possible end-to-end transmission delays. The integration of opportunistic networking and MCNs represents then an interesting option in the case of services deemed to be delay tolerant. According to the Cisco's global mobile data traffic forecast for 2014-2019, delay tolerant services represent some of the most popular applications driving the mobile data growth, and include, among others, email, file sharing, social networking, software/firmware updates, mobile video, cloud services, data metering and goods tracking. In this context, this section presents a novel strategy to integrate opportunistic networking into device-centric MCNs in order to improve energy efficiency by exploiting opportunistic principles and the services' delay tolerance. The study focuses on a 2-hop uplink MCN scenario where a static SN (Source Node) wants to upload a message of size F to a BS before a deadline T. To this aim, the SN can first establish a D2D link with an MN that stores and carries the information before forwarding it to the BS. A key process in the integration of opportunistic networking and MCNs is therefore the adequate selection of the MN. In [5], it was shown that selecting the MN that is located closest to the BS can reduce the time needed to upload the information to the BS and hence the cellular transmission energy consumption. However, it could not compensate the high D2D transmission energy consumption levels that result in inefficient end-to-end transmissions. The authors then proposed in [5] an analytical optimization framework that derives optimum locations at which D2D (SN to MN) and cellular (MN to BS) transmissions should take place in order to minimize the energy consumption while satisfying the service QoS requirements. The optimization framework assumes an MN can be found when needed at the derived location (Opt_X_i), which can actually not always be guaranteed. To deal with this issue, the authors propose AREA, an opportunistic forwarding scheme [6] that increases the search area where to look for potential MNs around the identified optimum location Opt_X_i. The MN search area is computed using cellular context information, in particular statistical information about the spatial density and the distribution of nodes within the cell.

AREA estimates the probability to find at least one MN around *Opt_X*$_i$ when mobile nodes are uniformly distributed in a cell using a Poisson distribution:

$$P_{Opt\_X_i} = P\left(x > 0; \frac{\kappa}{R}\cdot\phi\right) = 1 - \exp\left(-\frac{\kappa}{R}\cdot\phi\right), \forall Opt\_X_i \in (1,...,R) \quad (1)$$

where *k/R* is the average spatial density of mobile devices within the cell of radius *R*, and *Ø* represents the diameter of the MN search area (equal to 2*r*). The radius *r* that guarantees with probability δ the presence of at least one MN around *Opt_X*$_i$ can be computed as:

$$r = \frac{R\cdot\ln(1-\delta)}{-2\cdot\kappa} \quad iff \ \exists\, Y'_i = \underset{\forall X'_i \in o(Opt\_X_i, r)}{\arg\min} \left(\vartheta(...)\right) \quad (2)$$

In addition to guaranteeing with probability δ (set to 0.9 in this study) the presence of at least one MN, the search area radius (2) requires the optimization framework [5] (represented by ϑ in (2)) to provide the location at which the MN has to start the cellular transmission (*Y'*$_i$) for every possible location of the MN (*X'*$_i$) within the search area. If these conditions are not met, SN will transmit the information directly to the BS using a traditional single-hop cellular connection. Equations (1) and (2) have been obtained considering a uniform distribution of nodes within the cell. The same expressions can be used for non-uniform distributions in scenarios where the cell is divided into rings and the spatial density of users per ring is known. This is actually the case for LTE (and HSPA) that divides cells into concentric rings where users utilize different transmission modes. In this context, the radius *r* around *Opt_X*$_i$ can be computed for non-uniform distributions of nodes within the cell replacing *k*/*R* in (2) by φ_i/l_r^i. φ_i represents the average number of nodes in the ring *i* where *Opt_X*$_i$ is situated, and l_r^i the ring length.

The evaluation of the AREA proposal considers that cellular links use LTE at 2GHz and D2D links use IEEE 802.11g at 2.4GHz. Details about the cellular LTE and D2D IEEE 802.11g throughput models used to solve the optimization problem can be found at [5]. The study uses the WINNER B1 model for urban scenarios and low antennas height (D1.1.2 WINNER II channel models) to estimate pathloss and energy consumed in the D2D and cellular transmissions. The energy consumption is also computed taking into account the energy consumed by storage units at mobile devices as detailed in [5]. The study considers MNs are uniformly distributed in a cell with a radius of 800m (the spatial density of MNs is *k/R*=0.09MNs/m). We consider MNs are in line with the BS, and move towards the BS with a speed of 2m/s. The evaluation scenario considers that a static SN needs to upload a file of size *F*=10Mb before a deadline *T*=60s.

The energy gains that opportunistic device-centric wireless networks can achieve across a cell are illustrated in Fig. 2. Fig. 2 represents the energy efficiency as a function of the distance between SN and BS. The energy efficiency is computed, following the ETSI ES 203 228 standard, as the ratio between the delivered data and the energy consumed for such delivery. The figure shows that the integration of opportunistic networking and MCN can achieve significant energy gains compared to traditional single-hop cellular communications from distances higher than 150m. The major gains are obtained with the optimum (but not always feasible) configuration [5]. The results obtained show that AREA can also significantly improve the energy efficiency compared to single-hop cellular communications, and obtain energy gains close to that obtained with the optimum configuration. For example, when SN is located 300m away to the BS, AREA reduces the energy consumption by 70% compared to single-hop cellular communications. The energy gains achieve with AREA further increase with the distance between SN and BS. In particular, AREA can reduce the energy consumption compared to single-hop cellular communications by 90% for SN distances to the BS higher than 500m. It is important noting that these gains are aligned with the 5G objectives in terms of energy efficiency.

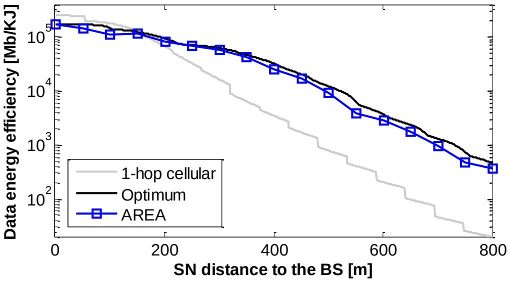

Fig. 2. Energy efficiency.

IV. CONCLUSIONS

Device-centric wireless networks (including D2D and MCNs) represent interesting alternatives to traditional cell-centric solutions, and are being considered as part of the 5G ecosystem. Device-centric wireless networks have the potential for significant capacity, energy-efficiency and QoS gains. This is expected to be achieved by means of exploiting the increasing computing, storage and connectivity capacity of smart mobile devices that will play a more active role in network management. This paper has experimentally demonstrated the potential of device-centric MCNs to overcome certain limitations of traditional single-hop cellular communications. The paper has also demonstrated how opportunistic networking and device-centric MCNs can be efficiently integrated to help achieve the 5G goals, in particular in terms of energy efficiency.

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