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Context-Aware Opportunistic Networking in Multi-Hop Cellular Networks

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Abstract – 5G networks will be required to efficiently support the growth in mobile data traffic. One approach to do so is by exploiting Device-to-Device (D2D) communications and Multi-Hop Cellular Networks (MCNs) in order to enhance the spectrum re-use and offload traffic over underlay networks. This study proposes to further improve the efficiency of transmitting mobile data traffic by integrating opportunistic networking principles into MCNs. Opportunistic networking can exploit the delay tolerance characteristic of relevant data traffic services in order to search for the most efficient transmission conditions in MCNs. The study first presents an analytical framework for two-hop opportunistic MCNs designed to identify their optimum configuration in terms of energy efficiency. Using this reference configuration, the paper then proposes a set of opportunistic forwarding policies that exploit context information provided by the cellular network. Numerical and simulation results demonstrate that opportunistic networking can significantly contribute towards achieving the capacity and energy efficiency gains sought for 5G networks. Under the evaluated conditions, the obtained results show that the proposed schemes can reduce the energy consumption compared to traditional cellular communications by up to 98% for delay tolerant services. In addition, the proposed schemes can increase the cellular capacity by up to 79% compared to traditional cellular communications.

Keywords – Multi-hop cellular networks (MCN); opportunistic networking; device-centric wireless; D2D; 5G.

1. Introduction

5G networks will face significant challenges to support the expected growth (by a factor of 500 to 1000) in mobile traffic in the next decade [1]. Such growth levels are expected to come from a 10 times increase in broadband mobile subscribers, and 50-100 times higher traffic per user. Leading international organizations also expect that 5G networks should support, compared to current 4G networks, 10 to 100 times more connected devices, 10 to 100 times higher user data rates, and 5 times smaller end-to-end latency. All this should be achieved while saving up to 90% of energy per provided service [1]. These expectations and forecasts have launched the race towards the definition and design of efficient future 5G networks. Relevant efforts currently focus on the use of higher frequency bands, the dense deployment of small cells and

where $\varnothing(\xi)$ represents the probability density function of the standard Normal distribution. The Normal distribution of a random variable x characterized by the parameters s (mean) and σ^2 (variance) can be expressed as [35]:

$$P\left(x; s, \sigma\right) = \frac{1}{\sqrt{2 \cdot \pi \sigma}} \exp\left(-\frac{\left(x - s\right)^2}{2\sigma^2}\right), \quad -\infty \le x < \infty \tag{18}$$

In eq. (17), Z represents the Cumulative Distribution Function (CDF) of x varying within an upper ($b \setminus x \in [-\infty, b]$) and lower ($a \setminus x \in [a, \infty]$) bounds:

$$Z = \Phi\left(\frac{b - s}{\sigma}\right) - \Phi\left(\frac{a - s}{\sigma}\right) \tag{19}$$

with the CDF defined as:

$$\Phi\left(x\right) = F\left(x\right) = P\left(X \le x\right) = \int_{-\infty}^{x} P\left(x; s, \sigma\right) dx \tag{20}$$

Using eq. (17), it is then possible to calculate the probability to find one MR at the identified optimum MR location (Opt_X_i):

$$P_{Opt\_X_i} = \int_{Opt\_X_i - \varepsilon/2}^{Opt\_X_i + \varepsilon/2} P(x; s, \sigma, a, b)\, dx \tag{21}$$

where ε represents the spatial discretization unit. Using eq. (21), the average spatial density of nodes at Opt_X_i can be expressed as $\mu_{Opt\_Xi}=(\mu/R)\cdot P_{Opt\_Xi}$, where μ/R is the average spatial density of nodes in the cell. Following [37], the truncated Normal distribution can be approximated by a series of discrete Poisson distributions. In this case, the analysis for a non-uniform distribution of nodes within the cell can be treated similarly to the scenario where nodes were uniformly distributed within the cell (Section 4.1.1). As a result, we can calculate the time t the SN needs to delay the D2D transmission to guarantee with probability δ the arrival of an MR at Opt_X_i under non-uniform distribution of nodes within the cell as:

$$t = \frac{R \cdot \ln\left(1 - \delta\right)}{-\mu \cdot P_{Opt\_X_i} \cdot v} \quad iff \ \exists Y'_i = \underset{\tau'_{b-1} = \tau_{b-1} + t}{\arg\min} \left(\vartheta(\ldots)\right) \tag{22}$$

It is important noting that eq. (22) depends on P_{Opt_Xi}. This results in that t varies with the optimum MR location within the cell, which was not the case for uniform distribution of nodes within the cell (eq. (15) and (16)). Eq. (22) also requires that the optimization problem (ϑ) can find a suboptimum location (Y'_i) at which the cellular transmission should start. Otherwise, the SN would communicate with the BS using a traditional single-hop cellular connection.

4.2. Space-dependent Opportunistic Forwarding

The AREA proposal addresses the scenario in which an MR cannot be found when needed at the identified optimum location by increasing, around the optimum MR location, the search area where to look for potential MRs. The search area is defined using context information provided by the cellular infrastructure (spatial density and distribution of mobile nodes within

$$r = \frac{R \cdot \ln(1-\delta)}{-2 \cdot \mu} \quad iff \ \exists Y'_i = \underset{\forall X'_i \in o(Opt\_X_i, r)}{\arg\min} \left(\vartheta(...)\right) \tag{24}$$

Eq. (24) requires that for every possible location of the MR (X'_i) within the search area, the optimization problem (represented by θ in eq. (24)) is capable to find the location (Y'_i) at which the MR has to start the cellular transmission to the BS in order to minimize the energy consumption and guarantee that the transmission is completed before *T*. If it is not possible to find Y'_i for every possible X'_i within the search area, SN will transmit the information directly to the BS using a traditional single-hop cellular connection.

4.2.2. Non-uniform Distribution of Nodes within the Cell

The search area (defined by the radius *r* around Opt_X_i) has also been computed when the distribution of users within the cell is non-uniform. We consider again a non-uniform distribution in which the spatial density of nodes is higher close to the BS. This distribution is mathematically modeled by means of a truncated Normal distribution (eq. 17). Eq. (21) estimates the probability P_{Opt_Xi} that one MR is located at the identified optimum MR location. Using eq. (21), the probability to find one MR within the search area can be defined as a function of *r*:

$$P_{SearchArea}(r) = \int_{Opt\_X_i - \varepsilon/2 - r\cdot\varepsilon}^{Opt\_X_i + \varepsilon/2 + r\cdot\varepsilon} P(x; \mu, \sigma, a, b)\, dx \tag{25}$$

where ε represents the spatial discretization unit. If we consider that there are on average μ MRs within the cell, the probability to find at least one MR within the search area around the identified optimum MR location Opt_X_i can be calculated as $(1-(1-P_{SearchArea})^{\mu})$. The minimum radius r ($r \in \mathbb{N}$) around Opt_X_i that guarantees with probability δ the presence of at least one MR can then be defined using the following conditions:

$$\begin{aligned} &\left(1-\left(1-P_{SearchArea}(r-1)\right)^{\mu}\right) < \delta \\ &and \left(1-\left(1-P_{SearchArea}(r)\right)^{\mu}\right) \geq \delta \qquad iff \ \exists Y'_i = \underset{\forall X'_i \in o(Opt\_X_i, r\cdot\varepsilon)}{\arg\min} \left(\vartheta(...)\right) \end{aligned} \tag{26}$$

It should be noted that the same condition to the one analyzed in eq. (24) must be satisfied in eq. (26) in order to define the MR search area $o(Opt\_X_i, r\cdot \varepsilon)$. If the condition is not met, the SN will again transmit the information directly to the BS through a traditional single-hop cellular link.

5. Performance Evaluation

5.1. Worst Case Conditions

This section is aimed at numerically comparing the performance of the two proposed context-aware opportunistic forwarding strategies considering their worst case operating conditions. In particular, we consider that the DELAY scheme needs to wait for time *t* to elapse before a MR reaches the optimum MR location (*Opt_Xi*), and that AREA founds the MR at the limit of the search area. The evaluation under these worst case conditions allows identifying the minimum energy gains that the proposed strategies can achieve with respect to traditional single-hop cellular communications.

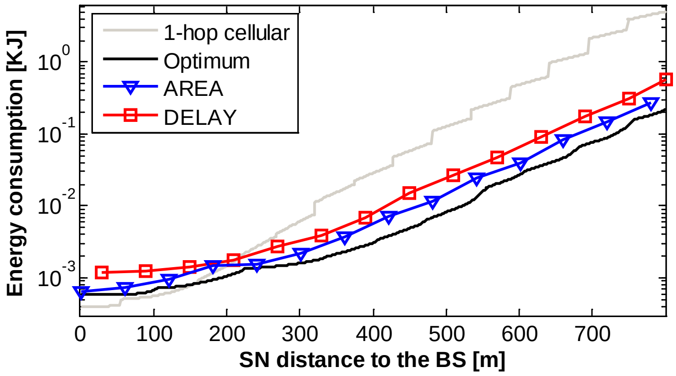
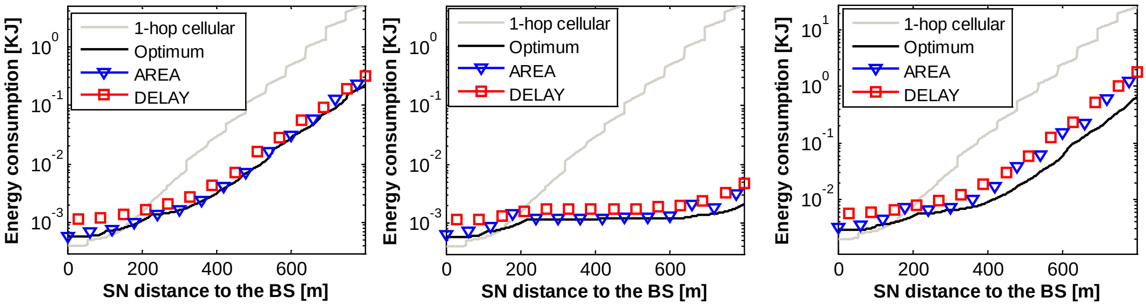


Figure 5. Total energy consumption (uniform distribution of nodes within the cell, *v*=2m/s, *T*=60s, *F*=10Mb, *μ/R*=0.03MRs/m).



a) *v*=2m/s, *T*=60s, *F*=10Mb, *μ/R*=0.09MRs/m

b) *v*=10m/s, *T*=60s, *F*=10Mb, *μ/R*=0.03MRs/m

c) *v*=2m/s, *T*=60s, *F*=50Mb, *μ/R*=0.03MRs/m

Figure 6. Total energy consumption (uniform distribution of nodes within the cell).

Figure 7 compares the total energy consumed when MRs are not uniformly distributed within the cell[5]; *μ/R* is set equal to 0.03MRs/m and the spatial distribution of users results in that approximately 68% of the nodes are located at distances to the BS smaller than 300m. A non-uniform distribution of users within the cell results in that *t* and *r* increase with the distance between SN and BS in order to compensate the smaller density of users when the distance to the BS increases. In this context, the AREA proposal considerably increases the energy consumed in the D2D transmission (and therefore the total energy consumption) with the SN distance to BS, and the DELAY proposal might exhaust the available deadline *T* without completely transmitting the file of size *F* because of the time it had to wait for an MR to arrive at the identified optimum location. It is important to remember that the current numerical evaluation considers a worst case scenario in which AREA selects the MR at the limit of the search area around the optimum MR location, and DELAY needs to wait for *t* to elapse before an MR reaches the optimum MR location. In any case, the results in Figure 7 clearly show that AREA and DELAY improve the energy consumption compared to traditional single-hop cellular communications. On average, AREA reduces the energy consumption compared to single-hop cellular communications by 40%, and DELAY by 26%. The benefits of the AREA and DELAY

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[5] The results are presented for SN distances to BS higher than 400m since the two schemes achieve very similar results for smaller distances.

The conducted evaluation of the context-aware opportunistic forwarding proposals has shown that AREA and DELAY can notably reduce the energy consumption compared to traditional single-hop cellular communications even under worst case conditions. This is observed for all scenarios and conditions (Figure 5 to Figure 8). The two proposals better approximate the energy performance achieved with an optimum configuration of opportunistic MCN communications under a uniform distribution of users. The results have also shown that AREA can reduce the energy consumption compared to DELAY under a uniform distribution of users in the cell. This trend is also generally observed under a non-uniform distribution of users within the cell; DELAY only achieves better energy performance at larger distances to the BS under certain conditions (high deadline *T* and MR speed).

5.2. Energy Efficiency

The previous section numerically evaluated the energy performance of the proposed context-aware opportunistic forwarding schemes under defined worst-case conditions. The conducted evaluation allows identifying minimum energy performance bounds. This section seeks to complement the previous study with an evaluation that covers various and more general possible operating conditions. In other words, the AREA scheme is not bounded to select an MR at the border of the search area, and DELAY does not have to wait *t* seconds before an MR is found at the optimum location. The AREA and DELAY proposals are also configured so that if no MR can be found at the identified locations and within the estimated timeframe, then SN directly transmits the information to the BS using traditional single-hop cellular communications. The evaluation here reported also includes additional reference schemes for comparison, and introduces variants of the AREA and DELAY schemes.

The AREA and DELAY variants are defined based on how the cellular infrastructure provides the context information required to calculate *t* and *r*. The original AREA and DELAY proposals described in Section 4 consider that the context information (spatial density and distribution of users within the cell) is provided per cell. However, this context information could also be provided for each concentric ring that defines a cell[6]. In this study, we consider a total of 15 rings per cell with each ring characterized by the use of a different LTE transmission mode (see Section 3.3). When the context information is provided per ring rather than per cell, we denote the context-aware opportunistic forwarding schemes as AREA-Ring or DELAY-Ring. The original DELAY scheme and DELAY-Ring estimate *t* using the expression derived for a uniform distribution of nodes within the cell (eq. (16)). When the context information is provided per ring, the spatial density of users (μ/R) in eq. (16) is replaced by φ_i/l^i_r. φ_i represents the average number of nodes in the ring *i* where the optimum MR location is situated, and l^i_r the ring length. The average number of MRs within the cell can then be calculated as $\mu = \sum_{i=1}^{N} \varphi_i$ and the cell radius as $R = \sum_{i=1}^{N} l_r^i$, with $i \in \{1...N\}$ and *N* representing the number of rings in the cell (*N*=15 in this study). The original AREA scheme and AREA-Ring estimate *r* using the expression derived for a uniform distribution of nodes within the cell (eq. (24)). When the context information is provided per ring, the spatial density of users (μ/R) in eq. (24) is also replaced by φ_i/l^i_r. It should be noted that the AREA and DELAY variants utilize the same expressions of *r* and *t* under uniform and non-uniform user distributions.

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[6] Standards such as LTE or HSPA divide cells into concentric rings. Different transmission modes are used per ring based on parameters such as the signal strength or the Channel Quality Indicator (CQI).

experienced for the D2D transmission as a result of the need to wait for an MR to reach the optimum MR location[8].

Technique	*μ/R*=0.125 MRs/m		*μ/R*= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=10m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=60s
AREA	94.1	92.1	90.3	89.4
AREA – Ring	96.5	99.4	97.4	96.5
DELAY	93.0	96.7	79.1	89.0
DELAY – Ring	96.1	99.9	78.9	93.5

a) Uniform spatial distribution of MRs within the cell

Technique	*μ/R*=0.125 MRs/m		*μ/R*= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=10m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=60s
AREA	80.0	78.3	80.1	77.6
AREA – Ring	96.1	95.7	94.6	95.2
DELAY	80.9	85.9	67.0	76.5
DELAY – Ring	91.8	98.9	65.7	83.9

b) Non-uniform spatial distribution of MRs within the cell

Table 3. Hit rate: percentage of SN-BS links established using two-hop opportunistic MCN communications.

The results depicted in Table 2 show that a higher mobility of MRs improves the energy gains of AREA and DELAY, with the largest improvements obtained for DELAY. Increasing the MRs speed results in that the cellular transmission from MR to the BS will start closer to the BS where higher cellular data rates are possible. However, it can also negatively impact AREA if the distance between SN and the selected MR exceeds the D2D communications range. This risk increases at higher speeds, which explains the slight negative impact of the MRs' speed on AREA's hit rate (Table 3). These trends are observed under uniform and non-uniform distribution of users in the cell. However, non-uniform distributions of users in the cell reduce the energy gains of both schemes. A non-uniform distribution of users in the cell results in a lower density of nodes with increasing distances to the BS. A varying user density across the cell influences the estimation of the *t* and *r* parameters. Providing the context information per cell in the case of non-uniform MRs distribution cannot take into account this variation, and can hence result in frequent incorrect estimations of *t* and *r*. The results depicted in Table 3 show that when the distribution of users per cell varies from a uniform one to a non-uniform one, the hit rate decreases. AREA and DELAY do not establish opportunistic MCN links to transmit the information from SN to BS when they cannot find an MR at the identified locations and within the estimated timeframe. A lower percentage of SN-BS links established

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[8] For this scenario, the AREA and DELAY proposals show slightly lower energy performance than under worst case conditions (Section 5.1) where it was assumed that an MR was always found at the limit of the search area (AREA) or at the optimum MR location after *t* seconds elapse (DELAY). The numerical results here reported consider that if no MR can be found at the identified locations and within the estimated timeframe, then SN directly transmits the information to the BS using traditional single-hop cellular communications. This operational difference explains why these results do not have to be equal or higher than those reported in Section 5.1 under worst case conditions.

actually consumed even more energy than traditional single hop cellular communications (Table 2). This is due to the fact that selecting an MR as close as possible to the BS significantly increases the energy consumption in the D2D transmission due to the lower quality/efficiency conditions for the D2D link. Table 4 also shows that the '1-hop Direct-contact' reference scheme can increase the capacity compared to traditional single-hop cellular communications. However, its capacity gains are in general below the ones obtained with opportunistic forwarding schemes as it does not take advantage of the D2D transmission to start the cellular transmission closer to the BS. Similar trends are observed in terms of the impact of user density, MR speed, deadline *T* and context information (per cell or per ring) on the AREA and DELAY capacity performance and comparison (Table 4) as they were observed for the energy consumption (Table 2).

Technique	***μ/R*= 0.125 MRs/m**		***μ/R*= 0.03 MRs/m**	
	***F*=10Mb, *v*=2m/s, T=30s**	***F*=10Mb, *v*=10m/s, T=30s**	***F*=10Mb, *v*=2m/s, T=30s**	***F*=10Mb, *v*=2m/s, T=60s**
AREA	63.1	72.6	61.1	66.3
AREA – Ring	64.2	78.5	63.5	68.6
DELAY	61.1	76.1	49.3	62.8
DELAY – Ring	62.6	78.9	49.3	63.5
MR closest to BS	74.7	81.8	72.4	76.6
MR closest to SN	18.5	72.4	20.5	48.3
1-hop Direct-contact	41.1	73.6	41.1	48.3
Optimum	66.9	79.1	66.9	72.1

a) Uniform spatial distribution of MRs within the cell

Technique	***μ/R*= 0.125 MRs/m**		***μ/R*= 0.03 MRs/m**	
	***F*=10Mb, *v*=2m/s, T=30s**	***F*=10Mb, *v*=10m/s, T=30s**	***F*=10Mb, *v*=2m/s, T=30s**	***F*=10Mb, *v*=2m/s, T=60s**
AREA	42.2	50.5	43.2	45.7
AREA – Ring	63.0	76.7	57.7	65.1
DELAY	41.7	58.4	31.0	40.8
DELAY – Ring	51.6	76.9	33.9	61.2
MR closest to BS	73.7	81.6	63.9	70.2
MR closest to SN	25.4	73.5	36.6	53.7
1-hop Direct-contact	41.4	73.6	41.4	48.3
Optimum	66.9	79.1	66.9	72.1

b) Non-uniform spatial distribution of MRs within the cell

Table 4. Capacity gains with respect to single-hop cellular communications.

5.4. Simulations

This section extends the previous studies with the analysis of opportunistic MCN communications by means of simulations in NS2. Simulations can complement the previous numerical evaluations as they can account for relevant factors such as interference. Interference can be particularly relevant for D2D communications operating at the 2.4GHz ISM band. This study focuses on the AREA proposal since previous results already showed that AREA generally outperforms DELAY (see Section 5).

The simulator implements mobile nodes that use an IEEE 802.11g interface at 2.4GHz for D2D communications. The simulator includes the IEEE 802.11s' discovery process that is enabled through the periodic broadcast exchange of beaconing messages among neighboring nodes. Beacon messages include location information of the mobile nodes. Using the IEEE 802.11s' discovery process, mobile nodes keep updated tables of 1-hop neighbor nodes (including their locations) that are candidates to establish D2D links. This information is exploited by AREA to select the adequate MR within the search area. The simulator implements the WINNER pathloss model for urban scenarios (Section 3.2) and the 'store and carry' process (Section 3.4). The simulator implements an LTE cell with 15 concentric rings that coincide with the available CQI indexes in LTE (Section 3.3). The simulated scenario uniformly distributes mobile nodes within the cell. The nodes move towards the BS at 2m/s. The same scenario has been reproduced in NS2 and Matlab to confirm the trends observed in the numerical evaluations. The simulations also consider the case in which the SN wants to upload a file to the BS using a MR with store, carry and forward capabilities. However, the simulations consider simultaneous traffic sessions from different SNs. This allows accounting for the impact of interferences, which are expected to be particularly relevant for IEEE802.11-based D2D communications. A large number of simulations have been carried out varying the location of the SNs within the cell. The rest of parameters are summarized in Table 1.

Table 5 reports the reduction (in percentage) of the average energy consumption achieved with the AREA proposal compared to conventional single-hop cellular communications. The results are reported for simulations carried out in NS2 and the previous evaluations using Matlab. The results confirm for both evaluations that opportunistic MCN communications reduce the energy consumption compared to conventional single-hop cellular communications. The simulation results are shown for different simultaneous traffic sessions. This parameter refers to the number of simultaneous traffic sessions that take place while SN is transferring the information from SN to MR, and that can interfere this transmission (i.e. it is not related to the total number of simultaneous traffic sessions in the cell, but only considers those sessions that can interfere a transmission from SN to MR). It is important noting that the results obtained with a single interfering traffic session are in line with those reported in the numerical evaluations. This is the case because the operation of AREA is not affected by other simultaneous transmissions. In this case, the D2D link of the opportunistic MCN connection experienced, on average, a packet collision rate of 0.49% in the scenario characterized by the presence of a single traffic session. The packet collision rate has been measured as the ratio between the number of data packets that suffer collisions and the total number of transmitted data packets. Table 5 also shows that the energy benefits of AREA with regards to single-hop cellular communications slightly reduce when the simultaneous traffic sessions increase; the gains achieved are still higher than 90%. This slight decrease is due to higher interference levels experienced for the D2D transmissions that result in an increase of the packet collision rate. For example, the packet collision rate experienced in the D2D link is 3.3%, 4.8% and 7.25% when considering 3, 5 and 9 simultaneous traffic sessions, respectively. As the packet collision rate increases, the D2D link requires more time to conclude the transmission of the file since additional retransmissions are needed. The larger D2D transmission time and the retransmissions result in an increase of the D2D energy consumption.

Technique	Simulations				Numerical
	Simultaneous traffic sessions				
	1	3	5	9	
AREA	94.9	94.4	93.5	91.4	95.1
AODV	78.0	58.2	51.8	37.7	-

Table 5. Reduction (in percentage) of the total average energy consumption compared to single-hop cellular (uniform spatial distribution of MRs within the cell, *v=2m/s, T=60s, F=10Mb, μ/R=0.09MRs/m*).

Additional simulations were performed considering the case in which the SN to BS transmissions were done using ad-hoc routing protocols, in particular using the AODV (Ad hoc On-Demand Distance Vector) protocol [42][10].

The results reported in Table 5 show the reduction (in percentage) of the average energy consumption achieved with the AODV protocol compared to conventional single-hop cellular communications. The obtained results show that AODV can reduce the energy consumption, with the benefits decreasing with the number of simultaneous traffic sessions. These simultaneous sessions, and the resulting interference, have a higher impact for AODV than for the AREA proposal that benefits from the store, carry and forward process. This is the case because AODV requires multiple intermediate D2D transmissions to communicate SN with the BS (the number of hops increases with the distance of SN to the BS). In this case, the interference and packet collisions have an impact on the quality experienced in each hop between SN and BS. The packet collision rate experienced in the AODV multi-hop routes was 2.9%, 6.6%, 10.8% and 15.2% when the number of simultaneous traffic sessions was equal to 1, 3, 5 and 9, respectively. These values are significantly higher than those observed for the AREA proposal that can provide higher energy gains than ad-hoc routing protocols such as AODV.

6. Conclusions

This study has proposed and analyzed the integration of opportunistic networking principles into multi-hop cellular networks for the case of delay tolerant services. A set of context-aware opportunistic forwarding schemes for MCN communications are proposed that exploit the store, carry and forward capabilities of mobile devices. The proposed schemes are based on a reference optimum configuration of opportunistic MCN communications analytically derived with the objective to minimize the energy consumption. The set of derived schemes exploit context information available in cellular networks to identify adequate mobile relays taking into account the identified optimum configuration. If no MR can be found at the identified optimum location and time instant, the AREA proposal expands the MR search area around the optimum location using information about the spatial density and distribution of mobile nodes within the cell. The DELAY proposal uses the same context information to identify for how long the D2D transmissions from the source node can be delayed to find an MR at the identified optimum location. The conducted numerical evaluations have shown that the integration of

[10] The study does not limit the number of hops that AODV can utilize to establish the route from SN to the BS. Mobile nodes use their IEEE 802.11g interfaces in the route search process. Once the route has been established, mobile nodes communicate between them using IEEE 802.11g D2D transmissions. The last hop to the BS is carried using a LTE connection.

opportunistic networking principles into MCN yields significant energy savings and capacity gains compared to traditional single-hop cellular communications. The AREA proposal generally outperforms the DELAY scheme. Both schemes benefit from the provision of context information per ring rather than per cell. In this case, the proposals, and in particular the AREA scheme, can achieve energy and capacity performance levels close to those that could be obtained under an optimum configuration of opportunistic MCN communications. In this case, the context-aware schemes can reduce the energy consumption compared to traditional single-hop cellular communications by up to 98% for delay tolerant services, and increase the cellular capacity by up to 79%. These results demonstrate that opportunistic networking and MCN can significantly contribute towards achieving the capacity and energy efficiency gains sought for 5G networks. The authors are now working on the implementation of the proposed opportunistic forwarding policies in hardware units. The experimental work that is currently under preparation builds on previous experimental contributions from the authors ([8]and [10]) and other studies available in the literature. Of particular relevance is for example the opportunistic networking solution developed by Spacetime Networks Oy. The solution builds from the results of the Scampi European project. This project developed the Liberouter framework [43]-[44], a complete system that includes low-cost applications that transform mobile devices (Android-based) into routers to assist in message forwarding. As a future avenue of research the proposed opportunistic scheme can be deemed a natural fit in emerging C/U-split architectures, where control (C) and user/data (U) forwarding planes are physically and/or logically decoupled [45]. In split-architectures, a macro BS is responsible for the control plane and high capacity small cells are responsible for the forwarding plane; in that setting, the macro-BS could orchestrate delay-tolerant transmissions based on the store-carry and forward networking paradigm.

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