Evolution of cooperation in device-to-device communication

G.B. Colombo, S.M. Allen, R.M. Whitaker
School of Computer Science & Informatics
Cardiff University
Email: colombog, allensm, whitakerrm@cardiff.ac.uk

Y.J. Chun, S.L. Cotton, W.G. Scanlon
Institute of Electronics, Communications and IT
Queen's University Belfast
Email: y.chun, simon.cotton, w.scanlon@qub.ac.uk

***Abstract*—Device-to-device (D2D) communications are a promising paradigm to improve spectral efficiency in cellular wireless networks by enabling peer to peer communication. In particular, short D2D links can be used to relay data to reduce the burden on core infrastructure. However, this relies on some mechanism to either enforce or incentivise nodes to donate their resources in order to act as a relay without any guarantee that this will be reciprocated in the future. *Indirect reciprocity* has been well studied from the perspective of human behaviour, proposing mechanisms and conditions under which such behaviour naturally evolves. In this paper we consider D2D networks that formulate the decision to share resources as a *donation game* using a model of *social comparison* and examine the conditions under which cooperation evolves without the need for a central authority. Experimentation shows that the emergence of cooperation is sensitive to network conditions, such as node density and noise.**

I. Introduction

This paper explores the potentiality of cooperative schemes for wireless communication networks. Novel protocols can be introduced to exploit the Device to Device (D2D) communication paradigm that is fully supported by the current implementation of these networks and will be included into the future 5G standards [1], [2], [3]. This mode of transmission allows users to form links without routing to base stations, thus improving efficiency through spectrum reuse. Cooperative schemes for D2D communication have been proposed for existing networks including areas as *nodes relay*, *energy efficiency* and *resources and spectrum allocation* [4], [5], [6], [7], [8].

In the following we focus our attention to a *network relay* scenario in which nodes can gain *benefit* from the forwarding of their data packages by neighbouring nodes that cooperatively donate part of their resources, e.g. their energy reserves [9]. Here nodes are paying some form of *costs* in order to facilitate the overall diffusion of information and a more balanced reuse of resources over the network. When high levels of cooperation are produced the system can benefit from significantly increased transmission rate and overall performance, see [10].

The aim of this study is then to investigate D2D networks in which decisions to share resources are formulated in terms of economic games and examine the conditions under which cooperation can evolve spontaneously. Specifically, we consider a scenario of indirect reciprocity based on the *donation game* [11], [12] using a reputation model based on *social comparison* [13].

In these type of scenarios a node asks one of his neighbours to donate part of its own resources, thus incurring in an individual cost. Previous studies [14], [11] have shown that the emergence of cooperative behaviours in a network is ruled by the relation between costs and benefits during such cooperative actions. It has been reported that even a relatively low *cost to benefit* ratio - in the order of 0.5 - can trigger a degrade in the cooperative performance of the systems. This will lead to the majority of interactions resulting in rejections of the cooperative requests, with no overall benefits produced for the system. In these situations cooperation fails to emerge spontaneously and requires specific form of interventions from the network operator to be incentivised. These include forms of rewards towards cooperative actions and control over the resources of the individual devices, in order to produce overall benefits for the whole network.

We here consider a mobile D2D network composed by randomly distributed nodes, where nodes cooperative actions are implemented by a numerical simulation within an evolutionary framework. Nodes are interacting at each time step in triples representing a source node that is in need of transmission, a destination node and a relay node that can help forwarding the data to destination. We model cost and benefit as various functions of the distance between the source, relay and destination, allowing us to investigate the relationship between node density and the evolution of cooperation in abstract terms, while retaining applicabilty to wireless resources such as transmission power. This involves a donating cooperative action from the relay to the benefit of the source node. However, the latter is not required to commit any immediate reciprocating action neither is necessarily expected to return such donation in possible future encounters as these cannot be guaranteed by the dynamic nature of the network, in which a same pair of nodes may not have the chance of meeting again. These types of scenario are typical of *indirect reciprocity* and the emergence of cooperative behaviour in these cases has been object of scientific studies for over two decades [15], [16]. The evolution of cooperative behaviour in such situations where players are no longer assumed to take rational decisions and coordinate with each other cannot be achieved by simply tracking the history of interaction between nodes, in our case the mobile devices composing the wireless network. This instead requires the implementation of reputation schemes and - at higher levels - other incentives or punishment mechanisms

[17], [18], [19].

II. An Evolutionary Framework for Cooperation

We considered an approach based on game theory and numerical simulations within an evolutionary framework to model the problem as a *donation game* [14], [11], as adopted in the vast majority of the studies on indirect reciprocity [18]. A population of S individuals is initially generated assigning at random one out of a possible set of strategies to each individual. Subsequently, in each round two players are randomly paired and assigned the role of *donor* and *recipient* respectively, and an instance of the 'donation game' is played. If donating decisions are made the donor will incur a cost c while the recipient is receiving a benefit b with $b > c$. A number K of games is played, then the next generation starts with players reproducing themselves, in terms of the strategy that characterises them, proportionally to their fitness. This is set for each player i as the *payoff* accumulated within the generation $\sum b_i - c_i$. Mutation has also been introduced to allow each strategy to re-appear at any point in the simulation by changing, with a small probability μ, the strategy assigned to a player with any other among those available. In the current implementation we have considered 2000 generations G for a population of 100 individuals, each playing an average of 20 games for generation - for a total of $K = 2000$ games per generations - and a 1% mutation rate.

We implemented the reputation system originally introduced by Nowak and Sigmund [11] in which each node maintains a reputation as an 'image' value that is assumed known by the system and made available to other players. At the beginning of each generation all images are set to zero then can assume integer values within the specific range considered, spanning from a binary assessment to an unbounded integer range. In line with previous experimentation we have considered a finite integer range bounded between ± 5 [11], [14]. Individual fitness is also reset to zero at the start of a new generation.

A. Social Comparison Strategies

In the proposed strategies players' actions are based on *social comparison* principles, in which players take the decisions to donate by comparing the recipient's reputation with their own. This idea stems from the *social comparison* theory, see [20] that can effectively represent human behaviours in real world scenarios.

Social comparison is a known cognitive heuristic that applies judgements about one or more other individuals to set a standard to which others can be compared. Nodes can then identify others as either similar or dissimilar leading to further adaptation mechanisms [21]. This allows to differentiate among individuals, thus a player reputation can be seen as good to some users and bad for others, depending on their current reputation value.

Given a donor i and recipient j with reputations r_i and r_j respectively, donor i assesses the reputation r_j of j, against their own reputation, r_i, with three possible outcomes, establishing either: approximate similarity $(r_j - \Delta \leq r_i \leq r_j + \Delta)$, upward self-comparison $(r_j > r_i + \Delta)$, or downward self-comparison $(r_j < r_i - \Delta)$. The strategy for a node i is represented as a triple of binary variables (s_i, u_i, d_i) indicating whether or not i donates when similarity (s_i), upward comparison (u_i) or downward comparison (d_i) is observed by i in respect of j's reputation. This leads to eight possible strategies. There is flexibility in the definition of the similarity parameter Δ, which is set to zero for all the current experiments.

B. Reputation Assessments

An important role for the effectiveness of cooperative reputation schemes is played by the assessment of reputation after a donating or defective action. A basic *image scoring* was originally proposed in [11], [12], in which reputation is proportional to the number of donations given. This implements the *social norm* that 'a player's image is incremented by one unit when a donation is made and decremented by one otherwise'. However, this has been found not bearing the property of stability and other assessments have been considered more effective in subsequent studies. These include *standing* [22] that implements the norm of 'not decrementing the donor's image when defection occurs in light of a request from a 'bad' player of low reputation'.

Any of the possible assessments proposed in the literature for indirect reciprocity can be implemented with the social comparison strategies by adapting the corresponding social norm to the actions of cooperating to individuals that have respectively higher, lower, or similar reputation than the donor. These also include the so-called 'leading eights' assessment rules that have been proven to support evolutionary stability when applied to binary image scenarios [23].

The current work applies a variation of the *standing assessment* adapted to the proposed *social comparison strategies* defined as in the following. Firstly, we have considered unary increments or decrements of the reputation after a cooperative or defective action, in line with the original formulation in [11]. Subsequently the *social standing norm* has been defined and implemented following the rule of 'not decrementing the donor's image when defection occurs in light of a request from a player with *lower* reputation'. This also allows the application of the standing norm originally introduced in [22] for binary reputation systems to larger variable ranges of the reputation values - in theory any integer range.

III. Wireless Network setting

We consider a D2D network represented by a population of mobile nodes randomly distributed over a geographical area. At each iteration, the simulation selects nodes representing the source n_s, destination n_d, and potential relay n_r of a communication link. The relay node n_r acts as the *donor* in the evolutionary simulation while the source node n_s takes the role of the *recipient* of the donating action, as shown in Figure 2.

We define the potential cost and benefit arising from this cooperative interaction in terms of the amount of a given resource required to support each link. For simplicity, we assume that the resource $R(u, v)$ needed to maintain a link between u and v is a function of the Euclidean distance $d(u, v)$ between them, see Figure 1.

For a given triple (n_s, n_r, n_d) the benefit accrued at the source node n_s is defined as the resource saved by switching from a single-hop transmission $(n_s \rightarrow n_d)$ to relayed transmission $(n_s \rightarrow n_r \rightarrow n_d)$. That is, the benefit is given by some function $B(R(n_s, n_d) - R(n_s, n_r))$. If the potential relay accepts the request, the actual donation depends on the resource required to form the link $(n_r \rightarrow n_d)$ and the related cost can be defined by a given function $C(R(n_r, n_d))$.

In practice, the functions C and B may vary from node to node, due, for example, to different properties of their mobile device or the priorities of the use. For simplicity, in this paper we consider identical functions for cost and benefit apply at each node. We assume $C(R) \geq 0$ for all R, and that $B(R_1) \geq B(R_2)$ and $C(R_1) \geq C(R_2)$ if $R_1 \geq R_2$.

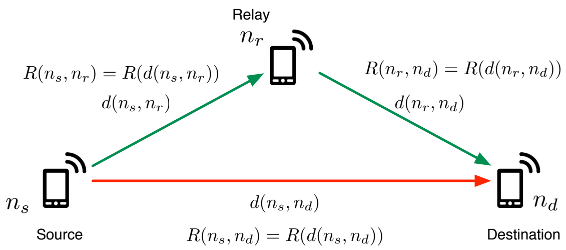


Fig. 1: Single relay three nodes scenario.

A. *Relay Selection*

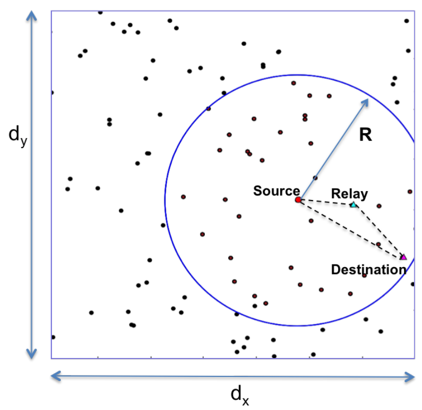


Fig. 2: Single relay three nodes scenario.

At each iteration of the simulation, representing one instance of the donation game, a source node n_s is selected uniformly randomly from all nodes in the population. A destination node n_d is then selected uniformly randomly within wireless range of n_s from the set $\{n : n \in S - \{n_s\}$ and $d(n, n_s) \leq R_t\}$, see Figure 2. If there is no such node in the transmission range, the current iteration is skipped with no further action. This represents a direct communication between source and destination with no contribution in terms of costs and benefits, in absence of any cooperative action between the nodes

As shown in [13], the evolution of cooperation is linked to low cost to benefit ratios. Selecting a relay at random could lead to either negative benefit (see locations R3 and R4 in Figure 3 for which the distance from source to relay is greater than that to destination) or very high cost to benefit ratios ($C/B >> 1$ as for the location R2 in the example, for which the cost value is not balanced by a large enough benefit).

For this reason, and supported by preliminary experimentation, we aim to select a relay that is close to the central point of the direct link between n_s and n_r (point M in Figure 3). That is, a node n_r that minimizes $d(n_r, M)$ and is also in range of both n_s and n_d: $d(n_s, n_r) < R_t$ and $d(n_r, n_d) < R_t$.

In order to prevent extremely high cost to benefit ratios, we add a further constraint that $d(n_r, n_d) < d(n_s, n_d)$, so that the cost of the relayed transmission must be lower than that of the direct transmission. While respecting this condition prevents negative benefit values it is still possible that relay selection could lead to cost to benefit values greater than one.

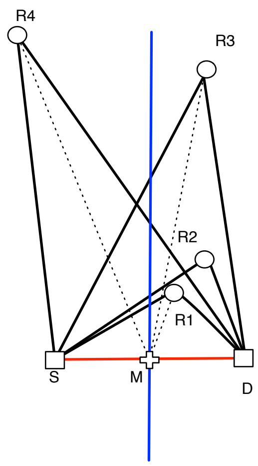


Fig. 3: Relay selection

Note that it is possible that the selected node is the destination node itself. This would represent a case where there is no benefit from relaying (given the selection constraints) for any relay within the transmission range. In these cases, the simulation skips the current iteration of the evolutionary algorithm, as no instance of the donation game can be performed.

In all other cases an instance of the donation game is performed between the source and relay node, with the source assuming the role of recipient and the relay that of the donor. Note that the only contribution of the destination is within the computation of the cost and benefit of the transaction. During the instance of the donation game the source issues a donation request to the relay, which will either perform a donation or a rejection according to the strategy followed and the nodes' relative reputation values.

The pseudocode of the entire procedure is given in Algorithm 1. In the algorithm the sub-procedure *playDonationGame* performs an instance of the donation game between donor and recipient while *updateReputation* assesses the reputation value of the donor according to the *social standing norm*, by comparing that of the recipient with its own. Subsequently procedure *createNewGeneration* generates the next population by asexual reproduction proportionally to the individual fitness values of the nodes, set equal to the cumulative *payoff* as described in Section II - see [13] for more details.

Algorithm 1

procedure $D2D - Evolution$
  input: Set of Nodes - S
    Geographical Area $L_x * L_y$
    Number of Generations G
    Number of Iterations K
  Locate nodes on the geographical area $L_x * L_y$
    by randomly assigning $x(n_i)$ and $y(n_i)$
  for g in G **do**
    Set $\forall i$ $rep_i \leftarrow 0$, *fitness*$_i \leftarrow 0$, *payoff*$_i \leftarrow 0$
    for for k in K **do**
      if k % $N = 0$ **then**
        $x(n_i)$ $y(n_i) \leftarrow$ Random($x(n_i)$,$x(n_i)$)
      Select source (*donor*) randomly
        $\{n_s : n_s \in S\}$
      Select destination $\{n_d : n_d \in S \setminus \{n_s\}$
        and $d(n_d, n_s) \leq R_t\}$
      Select relay (*recipient*) n_r as:
        $n_r \leftarrow min(d(n_r, M)$ and $d(n_s, n_r) < R_t$
        and $d(n_r, n_d) < d(n_s, n_d)$
      Calculate $C \leftarrow$ *Cost* and $B \leftarrow$ *Benefit*
      donation $\leftarrow$
        playDonationGame(n_r,n_s,rep_{n_r},rep_{n_s},C,B)
      rep_{n_r} rep_{n_s} $\leftarrow$
        updateReputation(n_r,n_s,*donation*)
      if *donation* is $True$ **then**
        payoff$_{n_r} \leftarrow$ *payoff*$_{n_r} - C$
        payoff$_{n_s} \leftarrow$ *payoff*$_{n_s} + B$
    Fitness(population) $\leftarrow$ Payoff(population)
    createNewGeneration(population)

IV. Experimental Results

The success of the evolutionary simulation is highly dependant on the ratio between costs and benefits of the relaying action as high values do not allow the emergence of cooperative behaviour in the network, see [13]. The following experiments explore the relation between the C/B ratio and operation level for different network conditions such as nodes density, level of noise, relation between resources needed and length of the wireless links, and relation between individual perception of the costs and benefits with the resources used.

We consider a network of 100 nodes, and vary its density by distributing them randomly in a range of square areas with sides $L_x = L_y$ between $50\,m$ and $400\,m$, resulting in a range of densities in the interval (0.04, 0.0006). To simulate devices' mobility we have in first approximation syncronised the changes of location of the nodes with the number of games played during the simulation. In particular, we randomly reshuffle the nodes locations $x(n_i), y(n_i)$ after they have played an average of one instance of the donation game. This results in a number of iterations equal to the size of the population.

The cost and benefit is expressed in terms of the resources needed to support links between the source, relay and destination. By defining this resource in terms of the link distance, we examine the relationship between node density and cooperation in abstract terms, also taking into account the potential for outage on the links. Scenarios are evaluated in terms of *average cooperation*, defined as the number of donations made as a proportion of the total number of games played at the end of the simulation, after G generations.

A. Experiment 1: Effect of noise and density

We first consider the resources required for a link between nodes u and v to be given by the function:

$$R(u, v) = d(u, v)^{\alpha} + N$$

This model of resource can represent, for instance, the required power transmission, as the Euclidean distance with the addition of a constant factor N to represent noise. We also assume that the *cost* and *benefit* of a donation are defined in first approximation as the resource function itself:

$$C(R) = R$$

$$B(R) = R$$

We then define N as:

$$N = \beta * C_o$$

where C_o is the average cost in absence of noise at each step of the simulation and β a scaling factor in the interval $(0, 1)$.

Hence, given a source node n_s and destination n_d with a potential donor n_r:

$$C(R(n_r, n_d)) = d(n_r, n_d)^{\alpha} + N$$

and

$$B(R(n_s, n_d) - R(n_s, n_r)) = d(n_s, n_d)^{\alpha} - d(n_s, n_r)^{\alpha}$$

resulting in a cost to benefit ratio of:

$$\frac{C}{B} = \frac{d(n_r, n_d)^{\alpha} + N}{d(n_s, n_d)^{\alpha} - d(n_s, n_r)^{\alpha}} \quad (1)$$

The aim of the experiment is to examine the cooperative behaviour of the network in response to variations of the parameter α and the density of the nodes over the network. This also depends on the noise N that has the effect of an extra cost added to the relay link to better represent the additional resources needed for the specific network environment.

Figures 4 and 6 show the relation between the network density, the scaling factor parameter β, and the average cooperation achieved in the network for values of α equal to 2 and 4. Figures 5 and 7 show the same effect applied to the *median* value of the cost to benefit ratio. All plots show an average out of five randomly seeded runs. We can observe that the value of the median increases with a decrease of the density and an increase in the noise ratio.

The decrease in cooperation with the lowest densities is related to the fact that in sparse networks there is a higher probability that a suitable relay cannot be found within the transmission range, resulting in the direct transmission as the only available option. This effect can be aggravated by the node mobility that in our simulation is implemented by randomly refreshing the locations of each node after each of them have participated, on average, to a single round of interaction, corresponding to one instance of the donation game. This result can be seen as counterintuitive as relaying over longer transmission distances is generally expected to produce higher benefits. However, this negative effect is mitigated when we relax the definition of the benefit $B(R)$ as a non-linear function of the resources.

In addition, we observe that the highest cooperation levels are not necessarily produced by the highest densities and lowest C/B. For example, Figure 6 shows a peak in cooperation for intermediate values of density and noise. This can be linked to the fact that very low levels of C/B can facilitate the appearance of higher frequencies of fully cooperative strategies but this also leaves the population more vulnerable to attacks from defectors, as shown in more details in the next experiments.

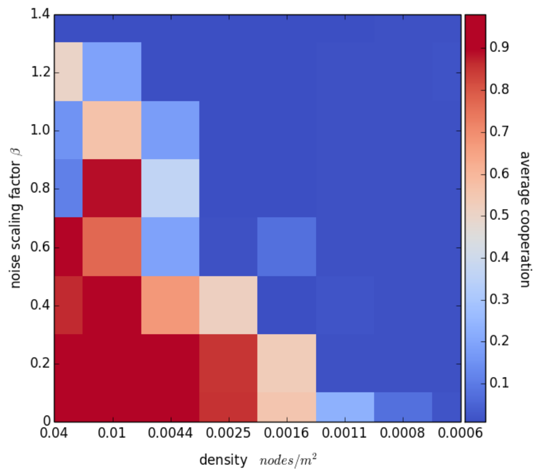


Fig. 4: Effect of network density and noise factor on the average cooperation for $\alpha = 2$.

B. Experiment 2: non-linear cost and benefit functions

This experiment investigates the effect of cost and benefit calculations as non-linear functions of the resource. We consider functions:

$$C = R^{\gamma_1} \; and \, B = R^{\gamma_2}$$

for a range of γ_1 and γ_2 values. The results are shown in Figures 9 and 10 obtained setting the noise level to zero

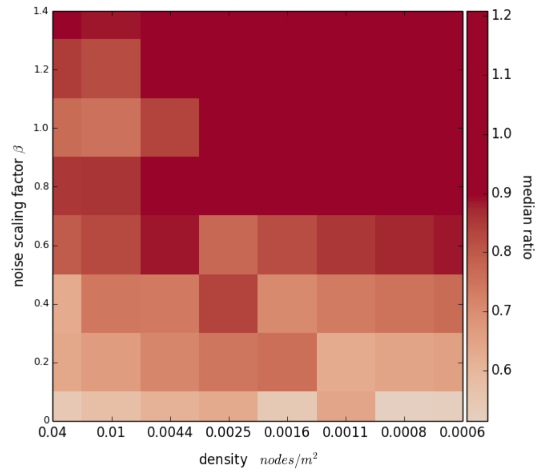


Fig. 5: Effect of network density and noise factor on the median value of the C/B ratio for $\alpha = 2$.

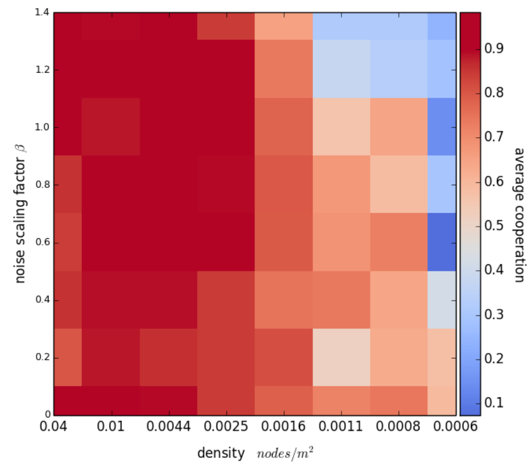


Fig. 6: Effect of network density and noise factor on the average cooperation for $\alpha = 4$.

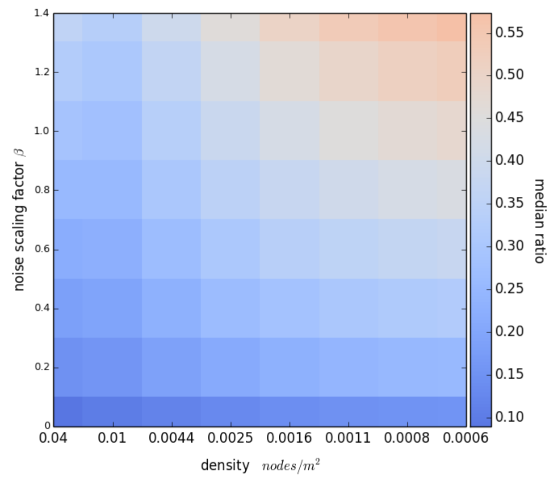
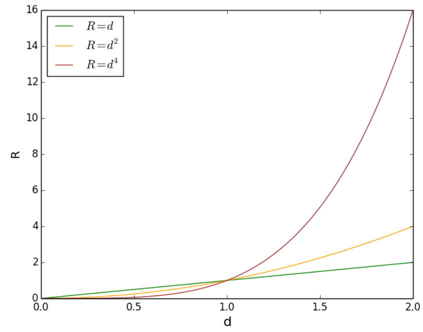
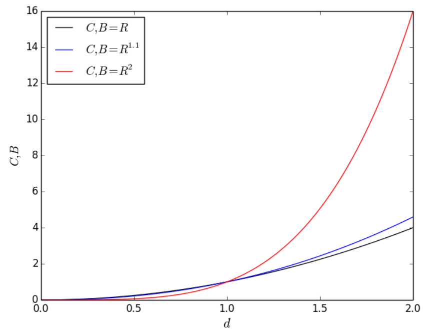


Fig. 7: Effect of network density and noise factor on the median value of the C/B ratio for $\alpha = 4$.



(a) $R = d^{\alpha}$



(b) $C, B = R^{\gamma}$

Fig. 8: Examples of functions C(R) and B(R)

($\beta = 0$) and $\alpha = 2$. We can observe that increasing the coefficient of the cost factor γ_1 from linear to more than linear produces a sudden drop in the cooperation level, as well as raising the cost to benefit ratio (in Figure 10 the row $\gamma_1 = 2$ and $\gamma_2 = 1$ is omitted as presenting very high ratio values in the order of hundreds). On the contrary, defining the benefit as a quadratic function $\gamma_2 = 2$ has the opposite effect of raising the cooperation levels and decreasing the cost to benefit ratio. Note that, as mentioned earlier, in these cases the negative effect of low densities is also considerably reduced and sparse networks appear able to maintain some degree of cooperation.

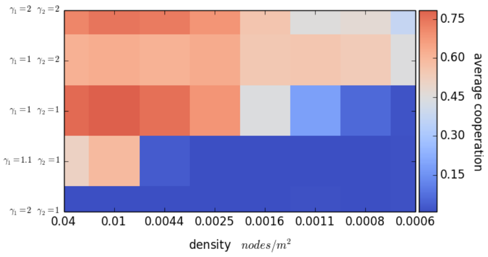


Fig. 9: Effect of the cost and benefit functions on the average cooperation in absence of noise and for for $\alpha = 2$.

However, the cooperation achieved for near zero values of the cost to benefit ratio appears lower that for slightly higher levels. This can be explained by the fact that when the cost of a donation is almost zero, then the dominant strategy

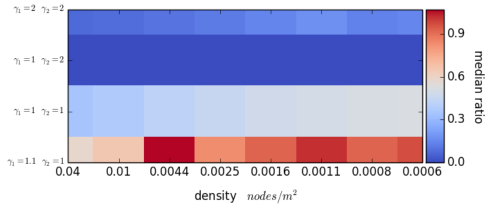
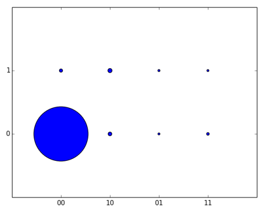
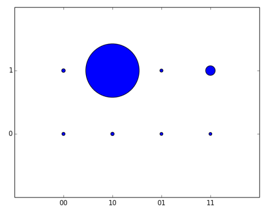


Fig. 10: Effect of the cost and benefit functions on the median value of the C/B ratio in absence of noise and for for $\alpha = 2$.

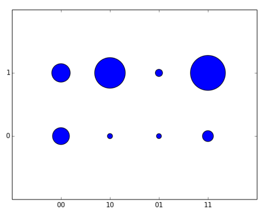
becomes unconditional cooperation - (1,1,1) with the notation in Section II-A. This strategy is, however, known to be more vulnerable to the invasion of defectors, such as the strategy (0,0,0). This can also be seen in Figure 11, that shows an example of the frequency of occurrences of the different social comparison strategies at the end of the simulation. Here the sizes of the bubbles represent the frequency of a given strategy, the y-axes the first 'gene' s_i of the triple representing the strategy (s_i, u_i, d_i) corresponding to donations (1) or defections (0) to opponents with similar reputation, while the x-axes the behaviours in the two remaining situations of opponents with higher or lower reputation (genes u_i and d_i), thus exhausting the whole range of eight possible behaviours. This result can be interpreted in a more general sense by observing that the use of functions that increase the benefit value (e.g from linear $\gamma_2 = 1$ to quadratic $\gamma_2 = 2$) does not produce any notable increase in the overall levels of cooperation.



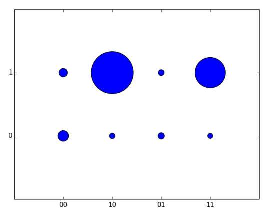
(a) $\gamma_1 = 2$ $\gamma_2 = 1$



(b) $\gamma_1 = 1$ $\gamma_2 = 1$



(c) $\gamma_1 = 1$ $\gamma_2 = 2$



(d) $\gamma_1 = 2$ $\gamma_2 = 2$

Fig. 11: Effect of the functions C(R) and B(R) on the frequency of the social comparison strategies at the end of the simulation.

C. Experiment 3: performance in presence of system error

The experiments presented so far implicitly assume that all communications within the relay scheme actually took place. In practice, links are subject to fading and other dynamic propagation effects that may hamper their operation. To take

Fading margin β	Outage o
0	0.5
0.2	0.25249
0.4	0.09121
0.6	0.02275
0.8	0.00383
1.0	0.00043
1.2	3.1e-05
1.4	1.5e-06

TABLE I: Relation between outage probability o and fading margin β.

into account a certain volatility in the successful formation of these links we add a *probability of outage* to the network model. This affects the emergence of cooperation, as we assume the source node cannot distinguish between cases where the relay cooperated but the link to the destination failed, or where the relay chose to defect.

Here the outage event is specified in terms of bit errors occurring during the relay transmission, causing the corresponding link to fail. We make the assumption that the received signal has an amplitude that varies with a statistical distribution - e.g Gaussian as a first approximation [24], [25]. Then outage is implemented by considering a *fading margin* element to the noise factor in the communication channel and so the resources needed for the transmitted signal according to the same given distribution.

The addition of noise has the effect to balance the probability of communication to fail under the threshold required to guarantee transmission, as it was assumed earlier on that the link was always valid once the relay had accepted to cooperate. We then assume a probability to fail that is associated to different values of the β scaling factor of the noise N, representing an additional margin added to the relay link, as shown in Table I. With the same probability we consider errors in the reputation model in terms of *execution error* in the implementation of the actual actions performed by the nodes. In other words the noise values shown in Figures 4 to 7 are now related to errors in the system in the execution of the cooperative actions, with the lower noise levels corresponding to the higher error rates and vice versa - for example zero noise is equivalent to the highest rate of error of 50%, see Table I.

Results in Figures 13 and 12 show now a decrease in cooperation for the lowest fade margins corresponding to high error rates, as for the highest noise levels this error is minimal or near zero according to the values in Table I. Although allowing a higher outage probability results in lower cost to the relay, thus encouraging cooperative behaviours, this is offset by the increase in error which means the relays reputation is decreased.

Note that there are no changes from Figures 5 and 7 in terms of cost to benefit ratio as in our implementation errors in execution only affect the computation of reputation and the consequent donating decisions. This has the consequence of losing the correlation between cooperative levels and cost to benefit ratios, as low C/B values can now correspond to poor cooperative performance due to the high error rates, whereas we have already observed a performance degrade due to high levels of noise-fade margin corresponding to high C/B ratios, see Section IV-A.

Note that a 50% error rate corresponds to the same percentage in cooperation probability, as we can expect a fifty-fifty split in requests ending with a donation. This virtually removes the correlation between high cooperation and high reputation values as the underlying assumption of the evolutionary model. As a consequence, we can observe in this case a 50% probability of cooperation as independent from different node densities and values of the C/B ratio.

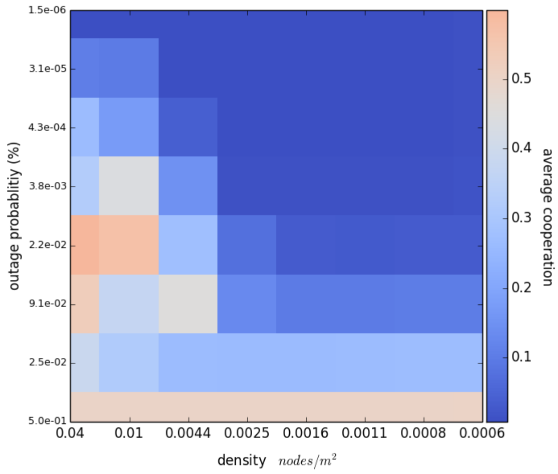


Fig. 12: Effect of network density and outage probability on the average cooperation for $\alpha = 2$.

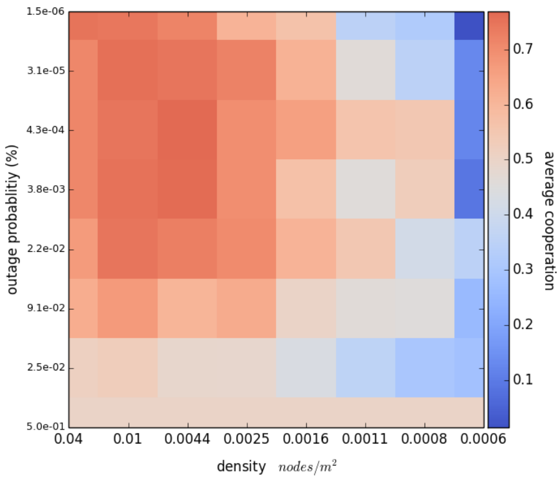


Fig. 13: Effect of network density and outage probability on the average cooperation for $\alpha = 4$.

V. Conclusion

This paper investigates the cooperative behaviour of Device-to-Device wireless communication networks through the application of an *indirect reciprocity* model based on *social comparison*. In particular we have here considered examples of D2D networks where decisions to share resources are formulated as a donation game using the reputation model proposed in [13]. This was applied to an evolutionary simulation that locates the mobile nodes of a wireless network over a geographical area with a basic relay scheme.

Our approach differs in principle from other studies that focus on 'the implications on the global network performance based on different models of cooperation' [10] while the primary contribution of this work is on the complementary study of 'the impact of different wireless properties and resources on the actual emergence of cooperative behaviour'.

The performance of the network in terms of cooperation levels depends on the value of the ratio between costs and benefits of the donating action. However, differently from the implementation in [13] that considered a fixed range of C/B values, these costs and benefits are now determined by the specific selection and relative location of the nodes involved in the cooperative action: the source node in need of transmission, the end-point of the transmission, and the relay node that performs a donating action by forwarding the data package on behalf of the source.

Results from a set of numerical simulations show that the cooperation achieved depends on the density of the nodes over the network area, with the assumption that the amount of resources needed for a donation increases with the power of the euclidean distance between the nodes, and the noise factor applied to the computation of the cost value. Sparse networks are producing the lowest cooperative levels but not necessarily the highest values are produced by the highest densities.

Our experimentation shows that, similarly to the theoretical case presented in [13], cooperation evolves even considering a more realistic model and high levels of it can be still maintained, although not in such a clean and well behaved fashion.

Furthermore, the individual's perception of the costs and benefits they receive from the cooperative action as a function of the resources donated has also a significant impact on the network performance. Relations that enhance the perceived benefit adopting a more than linear function of the resources do not seem to add any significant effect to the average cooperative levels achieved in the network, while mitigating the negative effect of low densities.

Finally, the presence of system errors in terms of *probability of outage* has the effect of removing the correlation between the cost and benefit ratio and cooperation achieved, as the lowest C/B produced by the lowest 'noise' values N are no longer producing significant cooperation levels due to the high probability of errors in the reputation model.

VI. Acknowledgements

This research is supported by EPSRC grant No. EP/L026074/1 in collaboration with Telefonica Europe plc, Keima Ltd and Samsung Research and Development Institute UK. We also acknowledge the centre of Advanced Research Computing at Cardiff (ARCCA) which has provided the resources for the experiments published in this paper.

References

[1] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *Communications Surveys & Tutorials, IEEE*, vol. 16, no. 4, pp. 1801–1819, 2014.

[2] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5g be?" *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 6, pp. 1065–1082, 2014.

[3] B. Bangerter, S. Talwar, R. Arefi, and K. Stewart, "Networks and devices for the 5g era," *Communications Magazine, IEEE*, vol. 52, no. 2, pp. 90–96, 2014.

[4] P. Li and S. Guo, "Literature survey on cooperative device-to-device communication," in *Cooperative Device-to-Device Communication in Cognitive Radio Cellular Networks*. Springer, 2014, pp. 7–12.

[5] Y. Cao, T. Jiang, and C. Wang, "Cooperative device-to-device communications in cellular networks," *Wireless Communications, IEEE*, vol. 22, no. 3, pp. 124–129, 2015.

[6] Y. Li, T. Wu, P. Hui, D. Jin, and S. Chen, "Social-aware d2d communications: qualitative insights and quantitative analysis," *Communications Magazine, IEEE*, vol. 52, no. 6, pp. 150–158, 2014.

[7] T. Irnich, J. Kronander, Y. Selén, and G. Li, "Spectrum sharing scenarios and resulting technical requirements for 5g systems," in *Personal, Indoor and Mobile Radio Communications Workshop 2013)*. IEEE, 2013, pp. 127–132.

[8] R. Hu and Y. Qian, "An energy efficient and spectrum efficient wireless heterogeneous network framework for 5g systems," *Communications Magazine, IEEE*, vol. 52, no. 5, pp. 94–101, 2014.

[9] R. Atat, L. Liu, J. Ashdown, M. Medley, and J. Matyjas, "On the performance of relay-assisted d2d networks under spatially correlated interference," in *Global Communications Conference (GLOBECOM), 2016 IEEE*. IEEE, 2016, pp. 1–6.

[10] Y. J. Chun, G. B. Colombo, S. L. Cotton, W. G. Scanlon, R. M. Whitaker, and S. M. Allen, "Social comparison based relaying in device-to-device networks," in *PIMRC 2016*, 2016, pp. 1–7.

[11] M. A. Nowak and K. Sigmund, "Evolution of indirect reciprocity by image scoring," *Nature*, vol. 393, no. 6685, pp. 573–577, 1998.

[12] ——, "The dynamics of indirect reciprocity," *Journal of theoretical Biology*, vol. 194, no. 4, pp. 561–574, 1998.

[13] R. M. Whitaker, G. B. Colombo, S. M. Allen, and R. I. Dunbar, "A dominant social comparison heuristic unites alternative mechanisms for the evolution of indirect reciprocity," *Scientific Reports*, vol. 6, 2016.

[14] O. Leimar and P. Hammerstein, "Evolution of cooperation through indirect reciprocity," *Proceedings of the Royal Society of London B: Biological Sciences*, vol. 268, no. 1468, pp. 745–753, 2001.

[15] R. Boyd and P. J. Richerson, "The evolution of indirect reciprocity," *Social Networks*, vol. 11, no. 3, pp. 213–236, 1989.

[16] M. A. Nowak and K. Sigmund, "Evolution of indirect reciprocity," *Nature*, vol. 437, no. 7063, pp. 1291–1298, 2005.

[17] K. Panchanathan and R. Boyd, "Indirect reciprocity can stabilize cooperation without the second-order free rider problem," *Nature*, vol. 432, no. 7016, pp. 499–502, 2004.

[18] H. Brandt, H. Ohtsuki, Y. Iwasa, and K. Sigmund, "A survey of indirect reciprocity," in *Mathematics for Ecology and Environmental Sciences*. Springer, 2007, pp. 21–49.

[19] B. Rockenbach and M. Milinski, "The efficient interaction of indirect reciprocity and costly punishment," *Nature*, vol. 444, no. 7120, pp. 718–723, 2006.

[20] A. P. Buunk and F. X. Gibbons, "Social comparison: The end of a theory and the emergence of a field," *Organizational Behavior and Human Decision Processes*, vol. 102, no. 1, pp. 3–21, 2007.

[21] B. Marsh, "Heuristics as social tools," *New Ideas in Psychology*, vol. 20, no. 1, pp. 49–57, 2002.

[22] R. Sugden, *The economics of rights, co-operation and welfare*. Blackwell Oxford, 1986.

[23] H. Ohtsuki and Y. Iwasa, "The leading eight: social norms that can maintain cooperation by indirect reciprocity," *Journal of Theoretical Biology*, vol. 239, no. 4, pp. 435–444, 2006.

[24] T. S. Rappaport *et al.*, *Wireless communications: principles and practice*. Prentice Hall PTR New Jersey, 1996, vol. 2.

[25] H. Hammuda, *Cellular mobile radio systems: designing systems for capacity optimization*. John Wiley & Sons, 1997.