Towards Trusted, Social-Aware D2D Connectivity: Bridging Across Technology and Sociality Realms

Aleksandr Ometov[†], Antonino Orsino, Leonardo Militano,
Dmitri Moltchanov, Giuseppe Araniti, Ekaterina Olshannikova,
Gabor Fodor, Sergey Andreev, Thomas Olsson, Antonio Iera, Johan Torsner,
Yevgeni Koucheryavy, and Tommi Mikkonen

May 16, 2016

Abstract

Driven by the unprecedented increase of mobile data traffic, device-to-device (D2D) communications technology is rapidly moving into the mainstream of fifth-generation (5G) networking landscape. While D2D connectivity has originally emerged as a technology enabler for public safety services, it is likely to remain in the heart of the 5G ecosystem by spawning a wide diversity of proximate applications and services. In this work, we argue that the widespread adoption of the direct communications paradigm is unlikely without embracing the concepts of trust and social-aware cooperation between end users and network operators. However, such adoption remains conditional on identifying adequate incentives that engage humans and their connected devices into a plethora of collective activities. To this end, the mission of our research is to advance the vision of social-aware and trusted D2D connectivity, as well as to facilitate its further adoption. We begin by reviewing the various types of underlying incentives with the emphasis on sociality and trust, discuss these factors specifically for humans and for networked devices (machines), as well as propose a novel framework allowing to construct the much needed incentive-aware D2D applications. Our supportive system-level performance evaluations suggest that trusted and social-aware direct connectivity has the potential to decisively augment the network performance. We conclude by outlining the future perspectives of its development across research and standardization sectors.

Introduction and Rationale

In recent years, we have been witnessing an increased proliferation of bandwidth-hungry user applications, which are becoming ubiquitous in the form of multimedia services, interactive games, and social networking solutions. To effectively cope with the resulting avalanche of mobile traffic, fifth generation (5G) networks demand innovative technologies capable of supporting the ambitious system requirements. To this end, unprecedentedly high targets were set for the 5G system design, such as seamless wide-area coverage (with 100 Mbps user rate) and extremely high-capacity hot-spot access (1 to around 10 Gbps user rate). Among the candidate 5G technologies, direct device-to-device (D2D) communications attracts an increased research attention [1] as it promises to deliver improved throughputs, provide more efficient spatial reuse, lead to extended network coverage, and enhance user energy efficiency. Broadly, D2D communications refers to a radio technology that enables devices to communicate directly with each other, that is, without routing the data paths through a network infrastructure.

With the widespread adoption of D2D communications, we expect the user devices to take a more active part in 5G service provisioning and, in some cases (e.g., in partial coverage situations), even assume some of the roles of the network infrastructure. In particular, they can aid in providing wireless connectivity such as offering D2D-based data relaying, proximity gaming, content distribution and caching, as well as other forms of cooperative communications. This paradigm shift from the conventional cellular model is driven by the natural progress in communications technologies: the user devices are decisively augmenting their capabilities, whereas the base stations (BSs) are becoming smaller as a result of the ongoing network densification [2]. Consequently, the original functional disparity between these key components of the maturing 5G ecosystem – the user equipment (UE) and the BS infrastructure – is gradually becoming blurred.

However, there remains a fundamental difference between the UE and the BS, which is rooted in the ownership rights of the corresponding equipment. Hence, cellular operators may become interested in employing user devices as an important asset in their networks, to benefit from their improved computational power, storage and caching capacity, wireless access and sensing capability, as well as efficient support for proximity services. Accordingly, adequate sources of motivation that facilitate the end-user decisions to lend their personal devices for the collective tasks need to be involved. In return, to compensate for the corresponding reduction in the networking and computation power actually available to the individual user, more capable network assistance protocols will have to be developed – guiding the UE toward the best opportunities to receive its desired service (e.g., user-in-the-loop [3] and similar concepts). This rationale brings into focus the role that social relations and interactions between an individual human user and its proximate neighbors may play in supporting the maturing D2D communications paradigm.

In the past, community-centric incentives were exploited frequently, which means agreeing to engage into direct connectivity to cooperate with other like-minded individuals in certain well-defined scenarios (such as a conference, concert, sports event, etc.). However, in order for this solution to scale to network-wide applications, operator-driven incentive mechanisms are strongly demanded, such as dynamic pricing technique in [4]. Indeed, recent D2D-centric studies are already exploring benefits from the integration between social and communications domains [5], but most existing work implicitly assumes that all the users are equally likely to cooperate and share data. However, this is not the case in practice as users acquire and own digital content based on their individual interests and may not be willing to expose it unless trust is established with a potential D2D partner. As a result, our main motivation behind this research is a possibility to construct a trustworthy 5G-grade D2D connectivity environment (see Fig. 1) featuring both the offline human interactions (i.e., driven by the user encounter patterns) as well as the online human interactions (i.e., driven by social applications similar to Facebook, Twitter, and LinkedIn).

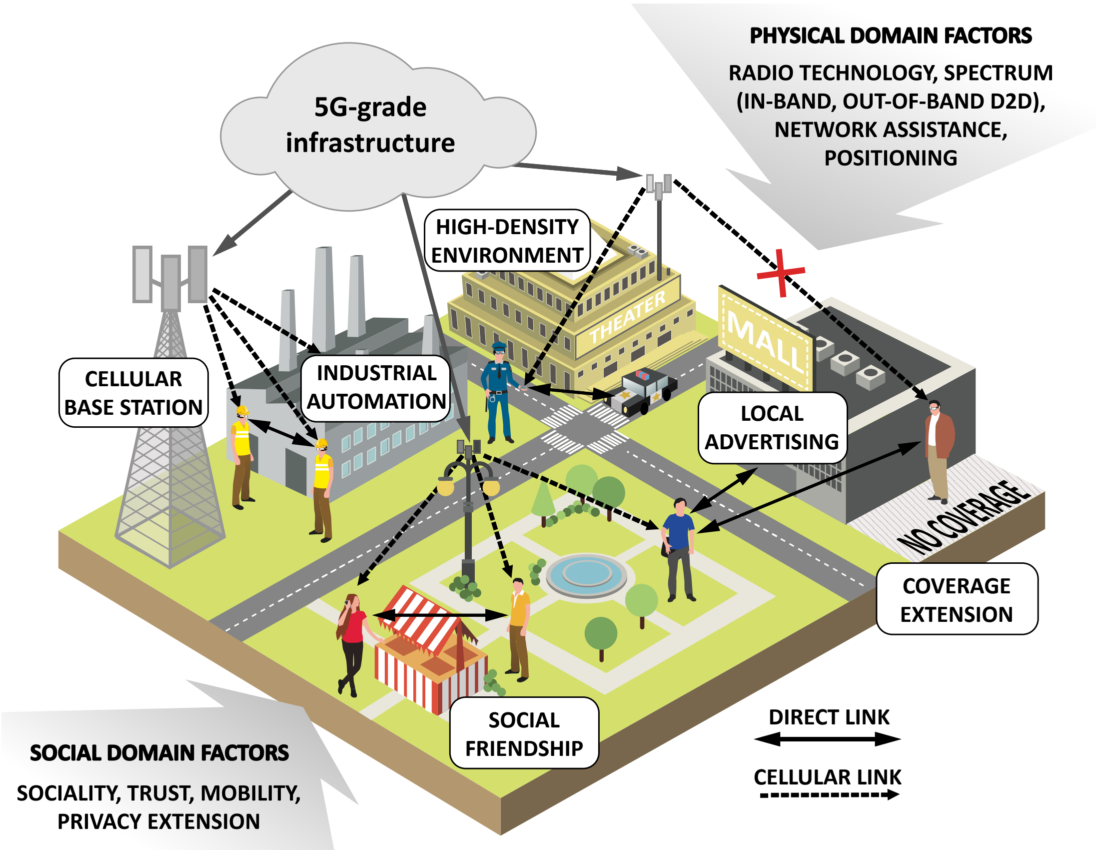

Figure 1: Urban network-assisted D2D applications.

In this work, we concentrate on introducing a novel layer of social awareness, which empowers the communicating devices to become the autonomously deciding entities. Our main objective is thus to explore how the two domains – the human social awareness and the D2D-enabled proximate connectivity – may interplay to improve the resulting communications performance (in terms of better system throughput) as well as achieve higher levels of service quality (in terms of better connectivity). These attractive improvements, together with the resulting growth in the UE energy efficiency, may therefore constitute the much needed incentives for the eventual user adoption of the promising D2D paradigm.

D2D Market and User Adoption

Presently, the 5G market is still at its developing stage indicating the projected *compound annual growth rate* (CAGR) of 58.2% during 2013-2020 [6]. In particular, future cellular networks are expected to be employed across a variety of market segments, including the proximity-based applications and multimedia services, along the avenues of public safety, social networking, and Internet of Things (IoT). As network operators have near-exclusive opportunities to handle the transmitted data, device location (proximity), and other user ecosystem information, we may expect the advent of a new generation of mobile services based on such context and proximity knowledge. However, direct connectivity is inherently constrained by certain real-life factors (such as contact time, location, duration of connectivity, user preferences, etc.), which makes it challenging to reach the critical mass of D2D users in today's networks [7].

With appropriate user adoption mechanisms, we envision the rapid proliferation of D2D communications scenarios, which would include not only public safety and emergency situations together with vehicle-to-vehicle information exchange for enhanced traffic safety, but also embrace commercially available pre-standard products that enable social networking and peer-to-peer communications outside of infrastructure coverage or in case of congestion. Although in these examples social awareness and the level of trust between communicating parties are markedly different, direct communications capability remains useful in terms of reducing latency, ensuring connectivity without infrastructure, improving reliability, and, ultimately, augmenting user experience.

To reach this vision, relevant contextual elements may be utilized to identify the typical behavioral patterns and stable interpersonal relationships of humans, thus aiding in matchmaking and timely formation of trusted user groups. For example, trust can be based on social media connections, since users within such networks are more likely to acquire similar content and share it with each other. However, important questions then emerge as to what would happen in larger heterogeneous coalitions consisting of both friends and strangers. In particular, to what extent the trust is transitive (trust to a friend of a friend) and does A trusts B and B trusts C imply A trusts C (similarly, does A trusts B and A trusts C imply B trusts C)?

In turn, D2D connectivity may impact the user-initiated activities as well as provoke or encourage external interactions (e.g., a service advertisement triggered from within the proximity range). Therefore, a key challenge behind the user adoption of D2D communications lies in understanding individual trust and privacy relationships, as proximity-based connectivity may generally lead to a lack of anonymity and confidence. Interestingly, user location history (e.g., in a form of joint movement patterns) may assist in determining social ties between the communicating users to establish the level of trust between them [8] (e.g., if users meet and travel together repeatedly, they are more likely to be familiar).

In summary, by monitoring the common contacts (including friend-of-a-friend and other weak ties), the system can augment its legacy trust establishment solutions. Yet, even these advanced approaches do not seem to completely satisfy the needs of 5G-grade trust-based D2D applications. To effectively stimulate user adoption, there has to be a meaningful value proposition for end customers. However, the existing marketing campaigns behind the next-generation D2D technology are primarily targeting operators/industry and thus do not appeal as much to masses of people. Therefore, the main question emerges: How can user adoption of D2D technology be incentivized effectively? Along these lines, we identify three possible levels of user incentives that may apply to specific D2D scenarios:

- *Pragmatic incentives:* typical user behavior is to remain *egoistic*, which means that the ultimate interest in using D2D technology should be proportional to the corresponding improvements in throughput, energy savings, and latency;
- *Indirect incentives:* D2D service providers potentially benefiting from the enhanced network performance may adopt new business models, where economic incentives (e.g., user's data plan discounts) are considered as rewards offered to users for lending the resources of their personal devices;
- *Social incentives:* the key motivation that can make the user drift from its egoistic behavior to *altruism* or *reciprocity* is sociality, where users lend their resources in order to assist friends, relatives, or other relevant peers. Here, the fundamental human needs of e.g., belonging, social reputation, and social usefulness could be considered to develop novel models of creating incentives.

Importantly, to mitigate the risks of user distrust and rejection, our envisioned ”social D2D” paradigm has to maintain high degrees of trustworthiness in data delivery among the connected D2D-capable UEs. This is particularly crucial whenever direct communications is utilized to extend the cellular coverage in cases when network connectivity becomes temporarily unavailable to the users (due to mobility, obstacles, disruptions, etc.). In what follows, we comprehensively outline how the above objectives can be achieved by the proposed social D2D paradigm. Then, we conduct a supportive system-level performance analysis of characteristic D2D applications, mindful of their trust requirements, that strongly emphasize the concepts of *human* and *device sociality* in the respective mobile data delivery process.

Bridging Across Technology and Sociality

We firmly believe that sociality has the potential to become a core incentive across a wide range of applications and services wherein D2D communications may demonstrate non-incremental benefits. However, the social domain should not be considered as a standalone enabling factor for proximate connectivity (see Fig. 1). By contrast, it needs to carefully match the respective technology constraints and features of the physical communications domain (such as the utilized spectrum, radio technology, battery/power resources, etc.). In this regard, our vision is in that not only human users and their social interactions are to be accounted for, but also the associated interactions between the user devices with their specific notion of sociality. This expectation is well supported by the recent research developments within the IoT community, which target to embrace the social networking concepts [9] to build trustworthy relationships among the devices [8]. In our present research (see Table I), we thus consider the two distinct types of sociality as described below.

Table 1: Social relationship factors between devices, possible applications, and the associated trust value.

Relationship	**Typology**	**Description**	**Applications**	**Trust value**
Human social relationship (HSR)	User-driven	Familiarity degree with friends/relatives/colleagues	Leisure applications, confidential data, eHealth, mission-critical communications	[0-1]
Market pricing relationship (MPR)	User-driven	Cooperative interactions with services triggered by the environment	Proximate marketing, proximity gaming, advertising	0.2
Ownership object relationship (OOR)	Device-driven	Relationship between objects owned by the same person	Personal cloud, smart home	1
Co-location object relationship (C-LOR)	Device-driven	Objects sharing personal experiences (e.g., cohabitation)	Information/data exchange at social aggregation points (concerts, sports events)	0.8
Co-work object relationship (C-WOR)	Device-driven	Objects sharing public experiences (e.g., work)	Information/data exchange at work aggregation points (e.g., fairs, workshops)	0.6

- *User-driven sociality*: in this case, humans are willing to interact and are directly controlling their social activities. The degree of how much two users are interested in exchanging data is characterized by a so-called *human social relationship* (HSR) factor, which may be linked to a social media tie, a family tie, etc. This measure is directly related to the level of familiarity and trust, according to which friends, relatives, or colleagues are likely to connect and share their content more frequently than the unfamiliar users. Within the same class of sociality, we may also consider the relationships based on the *market pricing relational* (MPR) model. The founding principle behind the MPR model is proportionality, as well as knowledge of how the relevant interactions are organized with respect to a common scale of values. In other words, the relationships established among people are driven by their willingness to interact or cooperate only in the light of achieving mutual benefits. In the literature, there are several examples that focus on smart surrounding scenarios for context-aware applications. For instance, triggers from the environment may invite and motivate people to socialize and/or cooperate, and thus take advantage of services within coverage (proximity market, gaming, advertising, etc.).

- *Device-driven sociality*: in this case, devices may autonomously interact according to the specific rules preset by the device owners and manufacturers – without an explicit user intervention during such interaction. Social relationships among the device owners are not necessarily required to foster this type of cooperation. To construct this sociality level, mobility patterns and relevant context can be considered to configure the appropriate forms of socialization [9]. Among these, the so-called *co-location object relationships* (C-LOR) and *co-work object relationships* (C-WOR) are established between devices in a similar manner as among humans, when they share personal (e.g., cohabitation) or public (e.g., work) experiences. Another type of relationships may be defined for the objects owned by a single user, which is named *ownership object relationship* (OOR) and may be of interest, for instance, when a number of devices belong to the same personal cloud.

Bridging across the realm of social-awareness and real-world D2D-based implementations, a factor of particular importance is dual mobility of the communicating entities. D2D application developers need to extend support for trust and confidence management to ultimately enable secure proximate communications that are aware of unrestricted human/device mobility. In this regard, the most challenging use cases are those, in which the out-of-coverage cellular devices are also becoming involved into the network-assisted D2D data exchange in the absence of a reliable link to the central trusted authority (residing e.g., in the operator cloud). In order to effectively address this and other aforementioned scenarios, our study investigates how human- and device-centric social relationships can achieve trusted connectivity in relevant D2D groups under realistic mobility as well as, possibly, partial cellular network coverage. In particular, we focus on three insightful study cases:

- *Trust-based human applications (Case A).* Interactions among humans with tight trust requirements are included here. In these study cases, the end-user is willing to reliably know which person the data are exchanged with. To this end, user-driven sociality is of paramount importance and sometimes even becomes the only acceptable enabler. Examples of such applications are found in work-related environments, such as construction sites as well as transport and cargo handling facilities in harbors or airports, where stringent safety regulations dictate increased levels of trust. Other applications may include confidential and mission-critical data collection, such as that for eHealth and safety applications.

- *Leisure and entertainment applications (Case B).* Connectivity between proximate devices supports applications for users at leisure, such as entertainment and gaming, non-confidential information sharing, and similar non-critical services (e.g., map sharing for intelligent transportation systems). These applications do not necessarily need an explicit social relation between the device owners, and trusted communications may rather be driven by the sociality of devices. Typical scenarios of interest in this category may consider users distributed in a certain area and sharing similar interests, such as content dissemination in a stadium, a university campus, or a pub, where matching people (in terms of interests, age, familiarity, etc.) interact by employing their devices.

- *Critical machine-to-machine (M2M) applications (Case C).* In the situations where, by definition, there is no (or, very limited) human intervention, automated device connectivity may still benefit from some form of social awareness. One may consider hazardous working environments, such as those often met in industrial automation scenarios, where large numbers of machines, sensors, actuators, or robots communicate mission-critical data. To facilitate such information exchange, trust can be delivered by operator-enforced incentives and policies, leading to optimized communications performance with higher degrees of security.

Social-Aware Framework for Trusted D2D

Our proposed social-aware framework aims at enabling trusted D2D-centric data delivery for proximate users in mobile environments. In these situations, direct links may (temporarily) extend or substitute cellular network connections, when the operator services become unavailable to (some of) the customers. Relevant clustering of the D2D devices can be conveniently modeled as a non-transferable utility (NTU) coalitional game $(\mathcal{N}, \mathcal{V})$, where $\mathcal{N}$ is a set of N players and $\mathcal{V}$ is a function, such that for every coalition $\mathcal{S} \subseteq \mathcal{N}$, $\mathcal{V}(\mathcal{S})$ is a closed convex subset of $\mathbb{R}^{|\mathcal{S}|}$. The latter contains the payoff vectors that the players in $\mathcal{S}$ can achieve, and $|\mathcal{S}|$ is the number of members in the coalition $\mathcal{S}$. The objective for the players in this NTU game is to maximize the value of the coalition they belong to. In the proposed framework, the utility for a coalition is defined as the degree of proximity and the strength of social relationships for the corresponding D2D-based cluster. To this aim, we define an NTU game, where for any coalition $\mathcal{S} \subseteq \mathcal{N}$ the value $v_i(\mathcal{S})$ associated with each player $i \in \mathcal{S}$ is determined as:

$$v_i(\mathcal{S}) = \sum_{j=1}^{|\mathcal{S}|} s_{i,j} \cdot p_{i,j} / |\mathcal{S}|, \tag{1}$$

where $s_{i,j} \rightarrow [0,1]$ is a function measuring the level of social relationships (or *friendship*) between a pair of communicating entities, whereas the second term $p_{i,j}$ is a binary function taking the value of 0 if the users i and j are not in proximity, and taking the value of 1 otherwise (by construction, we set $p_{i,i} = 1$). The resulting product of these two functions is then averaged across the players in a given coalition $\mathcal{S}$, thus always yielding a value within the range of $[0,1]$.

The actual definition of the social relationships level between the devices $s_{i,j}$ needs to allow for appropriate weighting of the contributions coming from human relationships and device sociality. Therefore, it may be defined as a weighted function $s_{i,j} = \alpha \cdot H_{i,j} + (1-\alpha) \cdot D_{i,j}$, where $H_{i,j} \in [0,1]$ is the degree of human-to-human sociality and $D_{i,j} \in [0,1]$ is the degree of device-to-device sociality. The social relationships between humans and devices are modeled based on the values shown in Table 1, where the "Typology" field identifies which class the social relationships belong to. The "user-driven" option corresponds to relationships that are being used to determine the value of $H_{i,j}$; the *HSR* and *MPR* relationships belong to this class. In contrast, the "device-driven" option identifies relationships that are used to determine the value of $D_{i,j}$; the *OOR*, *C-LOR*, and *C-WOR* relationships belong here.

Whenever two entities can be associated to more types of relationships of the same class, we select the strongest tie having the highest value [8]. The motivation for this is that stronger social relationships lead to higher probability of "trusted" connection, thus providing improved performance. Further, the weighting term $\alpha \in [0,1]$ is introduced into our model to adjust the respective contributions coming from the $D_{i,j}$ and $H_{i,j}$ terms according to a specific application and/or scenario. To this end, the two extreme cases with α equal either to one or to zero, are representative of only human- and only device-driven sociality scenarios, respectively, as holds for the applications discussed under study cases A (i.e., trust-based human-to-human scenario) and C (i.e., critical machine-to-machine scenario).

In summary, the study cases A and B discussed in the article represent two illustrative examples of the extreme situations with only human- and only device-driven sociality. In the third investigated scenario, study case B, the focus is on applications for users at leisure, where both human- and device-driven types of sociality are considered. In this case, the importance of the human- and device-driven sociality is assumed to be equal-weighted, which motivates the choice of $\alpha = 0.5$. However, other values of α may also be considered based on the scenario under consideration and the application in question. While a more thorough analysis of all possible scenarios remains out of the scope of this article, here we aim at proposing a powerful model that allows to explore how the human social awareness and the D2D-enabled proximate connectivity may interact to improve the resulting communications performance and service quality.

We can now define the value of $v(\mathcal{S})$ for a coalition $\mathcal{S}$ as the average degree of proximity and strength of social relationships for the users in the cluster: $v(\mathcal{S}) = \sum_{i=1}^{|\mathcal{S}|} v_i(\mathcal{S})/|\mathcal{S}|$. Importantly, the highest possible value associated with a certain coalition $v(\mathcal{S}) = 1$ is achieved if all of the devices are located in their mutual D2D coverage, as well as all of them enjoy the maximum level of friendship. In practice, the latter seldom happens in the *grand coalition* incorporating all the networked devices, and thus independent and disjoint coalitions are typically formed. To control the resulting stability problems, existing solutions proposed in recent literature can be adopted [10]. For instance, an iterative application of the merge and split rules enables the much needed convergence to a stable coalitional structure of the network.

Once stable D2D-clusters are formed, the D2D connectivity within them should be secured both in the cases of full and partial cellular coverage. Whenever connected reliably to the centralized network infrastructure, the D2D clusters can establish their information security rules by employing the conventional methods, hence relying on the operator infrastructure acting as a trusted authority. However, when cellular connection becomes unavailable, secure associations between D2D partners may benefit from solutions in [11] and [8], which enforce trustworthiness of human- and device-driven interactions, respectively.

Our Performance Evaluation Campaign

To validate the envisioned D2D framework and quantify the benefits of the proposed social-aware, secure clustering solution, a supportive system-level performance assessment has been conducted by utilizing our custom-made simulation environment, named WINTERsim[1]. Due to the need of modeling full-scale user mobility and application-level traffic, the underlying system-level evaluation methodology had to be streamlined, by simplifying the propagation and interference conditions, and thus employing the parameters summarized in Table 2. The output metrics of interest are aggregate effective throughput and corresponding device energy efficiency, as well as degree of connectivity, which indicates the proportion of users covered by cellular and/or direct links.

Our reference scenario features a tagged cellular BS (running the contemporary 3GPP LTE technology) deployed within a [150m×150m] area of interest, and having the coverage range

[1]WINTERsim system-level simulator: http://winter-group.net/downloads/

of 100m, resulting in around 70% of reliable cellular coverage available to the users. For the sake of completeness, we later consider several alternative values for the LTE coverage range – in order to understand the effects that it has on the degree of connectivity. Further, our communicating entities (humans and their connected devices) are allowed to freely move across the considered area of interest according to the characteristic "Levy flight" mobility pattern [12]. More specifically, we investigate the performance of a multimedia application with the packet size of 100 KB and the packet inter-arrival time of 10 s (e.g., video dissemination, eHealth, etc.). As for the D2D communications technology, discovery and connection setup functions are managed directly by the LTE BS with the appropriate network assistance protocols, whereas the actual direct data transmission is performed out-of-band (e.g., over WiFi-Direct links that can operate in parallel with LTE assistance, as they utilize the unlicensed spectrum).

The following alternative communications options are compared in our system-level study:

- *Cellular (LTE) solution.* A benchmark setup, where the connectivity is available only over the conventional cellular links, without any D2D-based transmission or coverage extension possibilities;

- *Simple D2D solution.* Only mobile devices under the reliable cellular network coverage may connect directly to form the D2D pairs according to the shortest distance between them. The BS is acting as the conventional trusted authority by guaranteeing trustworthy connectivity for all in-coverage D2D partners;

- *Advanced (social-aware) D2D solution.* Users may cluster together according to the proposed social-aware D2D framework. This may also happen under partial cellular network coverage, thus leading to D2D-based coverage extension. All connectivity (including the out-of-coverage links) is made trusted by taking advantage of the distributed information-security solution without a central trusted authority [11]. To further visualize the effects of both human- and device-driven sociality, we consider the three reference study cases and the associated α values as defined in Section : 1, 0.5, and 0 for study cases A, B, and C, respectively.

To ease further exposition, for the *baseline LTE* solution and the *simple D2D* scheme we only account for the portion of data transmitted by the users within the reliable cellular network coverage (by aggregating these effective values across individual users). In case of the *advanced D2D* solution, we additionally consider traffic of the out-of-coverage users enabled by our trusted, social-aware framework.

First, Fig. 2 indicates the achievable aggregate effective throughput as a function of the number of networked devices. Hence, we learn that at all times the proposed *social-aware D2D* solution outperforms the LTE-only alternative considered in this study, as well as the *simple D2D* solution. In particular, the case of $\alpha = 0$ (study case C, when only device-driven sociality is considered) achieves the best performance, followed by the cases when $\alpha = 0.5$ and $\alpha = 1$ (study case A, when only human-driven sociality is considered). This result suggests that the interactions based on the second level of sociality – those accounting for the relationships between the devices – may introduce significant benefits to the system operation, whenever the trust requirements of a running application allow for this.

Table 2: Core simulation parameters.

Application parameter	Value
Packet size	100 KB
Inter-arrival time	10 s
System parameter	**Value**
Cell radius	100 m
Maximum D2D range	30 m
WiFi-Direct target data rate	40 Mbps
LTE target data rate	10 Mbps
LTE BS Tx power	46 dBm
UE Tx power	23 dBm
Machine Tx power	0 dBm
D2D link setup time	1 s
Mobility model	Levy flight (with parameter 1.5 [12])
Number of UEs	[10-100]
$H_{i,j}$	[0-1]
$D_{i,j}$	[0.6,0.8,1]

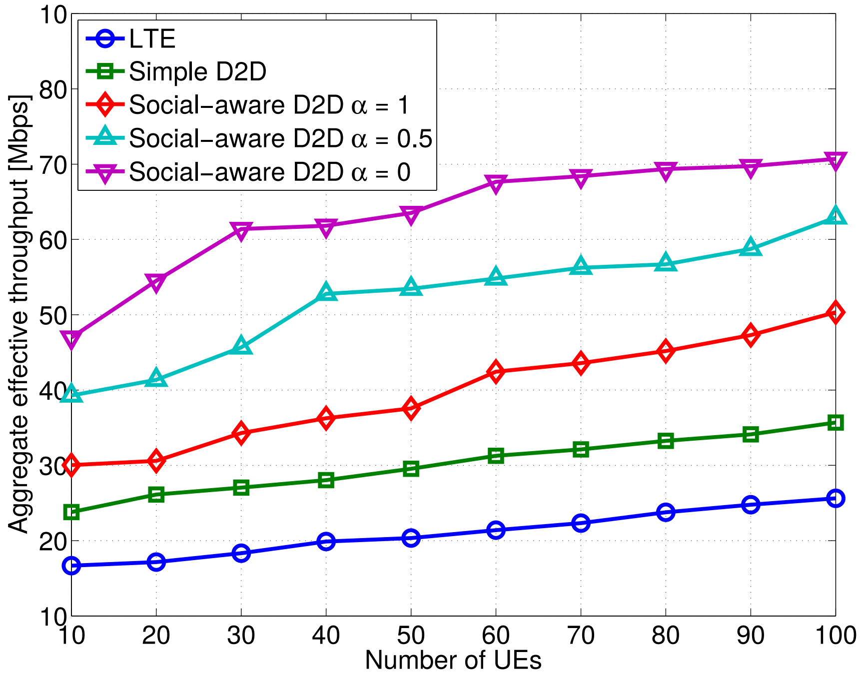

Figure 2: Impact of social relationships on the system throughput.

Further, Fig. 3 illustrates the degrees of connectivity offered within our area of interest, when a varying percentage of such area is covered by the LTE BS (eNodeB). In particular, the considered scenario corresponds to study case B (i.e., $\alpha = 0.5$), with 100 devices residing in the system. To this end, we measure the proportion of devices being served with the proposed *social-aware D2D* solution and compare it against the corresponding figure as achieved with the *simple D2D* scheme. As observed in the left subplot of Fig. 3, the proposed approach always demonstrates higher percentage of served users, with the benefits increased even further in the face of reduced LTE coverage. In particular, the proportion of served devices more than doubles with our social-aware operation, when the LTE coverage is only available over a half of the area of interest.

As observed in the left subplot of Fig. 3 indicates the overall proportion of users that are served in a given area by accounting for both the *simple D2D* and the *social-aware D2D* solutions in study case B (where $\alpha = 0.5$). Accordingly, we observe that a higher percentage of served users is reached when we consider a social layer of awareness among the devices and humans. Further, we learn that this positive effect is higher for lower degrees of LTE coverage.

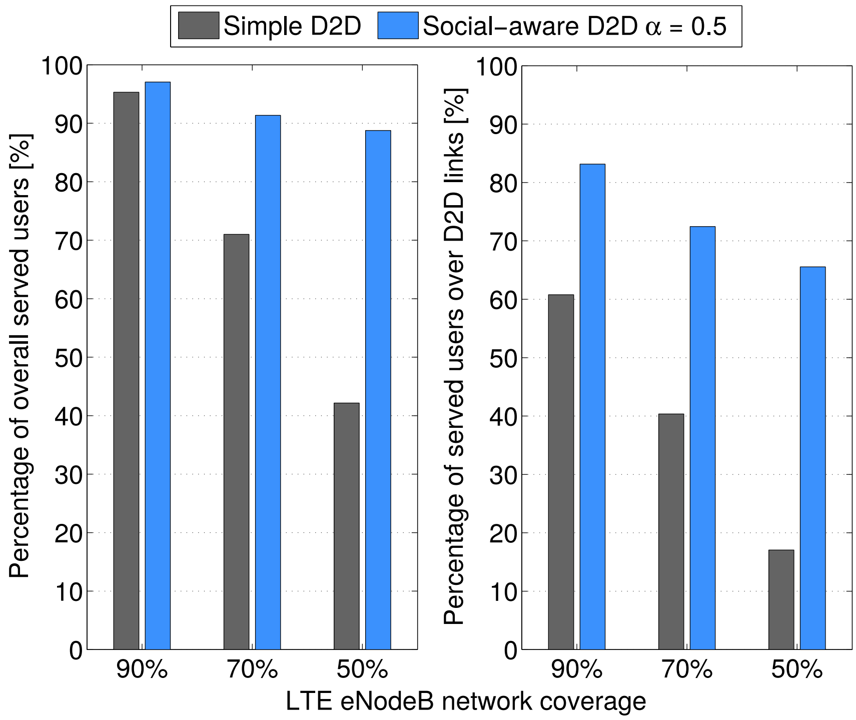

Figure 3: Impact of LTE coverage on the degree of connectivity in the system.

Further, in the right subplot of Fig. 3 we report on the proportion of users served with a simple D2D link (i.e., in case of *simple D2D* solution) or a D2D cluster (i.e., considering the proposed *social-aware D2D* solution). Clearly, this is a subset of the entire set of served users as it represents the share of users that either (i) prefer to establish a direct link instead of downloading the content over the LTE infrastructure, or (ii) can only be served over D2D connections in the locations where there is no LTE coverage. As we learn from this plot, when the available cellular coverage area is particularly small, in case of *simple D2D* solution the number of users that establish a D2D connection is low. This is due to the fact that under-coverage users reside in proximity to the BS and thus receive higher channel quality comparing to that on the D2D link. As a consequence, a higher number of users may be served through the infrastructure links with the LTE BS. On the contrary, the percentage of users served via D2D connections is three times higher for the proposed *social-aware D2D* solution. The explanation of this result is in that our solution is able to provide connectivity also to those users that are outside of the cellular coverage (i.e., within D2D clusters). Note that this important outcome is achieved owing to the operation of our social-based, secure cluster formation scheme.

In summary, in our model the LTE coverage and the user connectivity are tightly connected by the fact that by varying the area where the LTE infrastructure is present we arrive at different numbers of users that may be served over a cellular link with the LTE base station. In fact, as we can notice from Fig. 3 of the manuscript, when the LTE coverage is particularly low (i.e., only 50% of the area of interest) using a legacy LTE approach lead to a percentage of served users close to 40%.

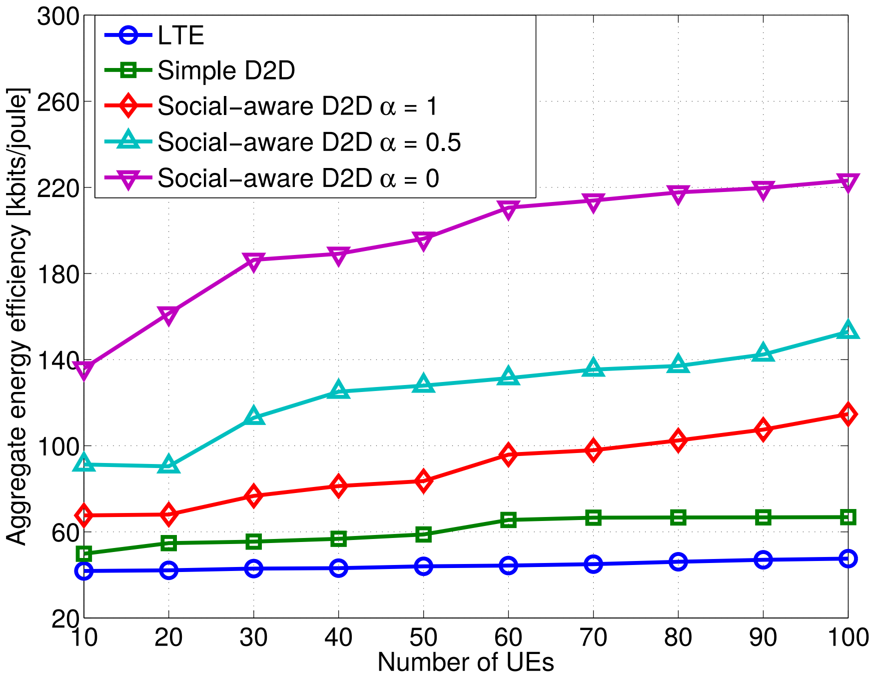

Figure 4: Impact of social relationships on the user energy efficiency.

Finally, performance results for the aggregate energy efficiency of user data transmissions are reported in Fig. 4. This metric has been evaluated by taking into account the relevant transmission power for each network node (refer to the values reported in Table 2). Again, the *social-aware D2D* approach outperforms both the considered *baseline LTE* and the *simple D2D* alternatives. In particular, for the case of $\alpha = 0$ our proposed solution reaches its highest gain by contrast to the benchmark LTE operation. This is due to lower transmit power of small-scale devices (i.e., connected machines) as compared to more power-hungry handheld UEs.

To conclude, our analysis indicates that social ties among both humans and their connected devices impact the ultimate performance of the proposed social-aware scheme that enables the trusted D2D clusters. In particular, with higher levels of social relationships, the resulting effective throughput grows, also yielding positive effects on the energy consumption of the devices and their degrees of connectivity. The key reason is that having better social relationships plays in favor of having larger coalitions between proximal humans/devices, even in the cases of partial cellular network coverage. Clearly, the improved throughput performance of our *social-aware D2D* solution is achieved at the cost of somewhat increased latency, as compared to the *simple D2D* scheme. Indeed, to deliver reliable connectivity to proximate humans/devices, especially outside of LTE coverage, more time-consuming security procedures are required to be executed in the UE. For instance, handheld devices need additional time to complete the security methods from [11], which leads to slightly higher latencies with the growing number of communicating entities. However, the implementation efficiency of said security mechanisms can be optimized further to reduce the computation time, which we leave for our subsequent study.

Standardization Aspects and Outlook

Historically, D2D communications capabilities and respective support for proximity services were first introduced in Release 12 of the 3GPP protocol suite [13]. Correspondingly, the main targeted use cases and associated system requirements are well-captured in the feasibility report (see 3GPP TR 22.803 document). It thus serves as a solid foundation for the development of enabling technology components, including device synchronization, service and device discovery, as well as actual direct communications – both under and outside of cellular network coverage. A direct consequence of the emerging D2D interface, the so-called *sidelink*, is the need to ensure interoperability of the devices produced by different vendors and, possibly, served by various cellular operators. Therefore, the appearance of the sidelink is a major advancement in the 3GPP architecture, affecting physical layer procedures, higher layers, and non-access stratum protocols alike[2].

While the initially considered set of D2D-related scenarios and requirements has been subdivided into public safety and general commercial use cases, Release 14 LTE networks are being prepared to additionally accommodate vehicle-to-vehicle and vehicle-to-infrastructure communications services (see 3GPP TR 22.885 document). We thus expect that as application developers, service providers, and user equipment manufacturers experiment with the rich capabilities offered by the D2D connectivity, further use cases will become attractive, including D2D-powered machine-type communications. Therefore, in 5G networks, we envision that the distinction between public safety and commercial applications will become blurred, thus making technology development (in the form of its components and end solutions) increasingly meaningful for in-coverage, partial network coverage, and out-of-coverage situations. In this context, our proposed D2D paradigm – enhanced with the involvement of social relationships established not only among familiar humans but also among familiar devices – will decisively contribute to the delivery of novel types of services over proximate links.

Among the many examples appearing on this scene, [14] already implements the discussed

[2]For details, see the following 3GPP specifications: TS 36.213, TS 36.300, TS 23.303, and TS 24.301.

concepts for intelligent transportation systems by exploiting the aforementioned vehicle-to-vehicle and vehicle-to-infrastructure communications services. Complementary to the research literature on the topic, there is currently a strong need for a broader standardization campaign. This may address such issues as, for example, (i) definition of categories for inter-device social relationships as well as rules for their triggering, (ii) common social-oriented interfaces and interaction models for users in pervasive D2D scenarios, (iii) distributed methodologies to enable secure data exchange among groups of humans/devices communicating over D2D links, possibly without a reliable connection to the centralized trusted authority, etc.

In summary, we are about to embrace the D2D communications as one of the key technologies within the rapidly maturing 5G ecosystem. It will broadly enable both the owners of advanced wireless devices as well as the smart and social IoT objects across diverse, pervasive platforms to effectively become a part of the cellular landscape. This, in turn, will pave the way to improved cellular service provisioning by e.g., offering D2D-based data relaying, content distribution and caching, or other forms of cooperative communications to augment the existing spectrum usage and device energy efficiency [15]. Another exciting research direction is to develop new mechanisms that take advantage of the unique position of cellular operators – with their well-developed infrastructure and pricing methods – to create incentives, win-win collaborative strategies, and ultimately raise social awareness among spectrum owners, network operators, and wireless device users. For 3GPP networks, the basic building blocks, associated protocol structures, and physical layer procedures are already being defined, while the creation of corresponding incentives and social awareness schemes that engage users as part of the service provisioning effort remains in strong need of further research.

Bibliography

[1] A. Asadi, Q. Wang, and V. Mancuso, "A Survey on Device-to-Device Communication in Cellular Networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014.

[2] I. Bhushan, J. Li, D. Malladi, D. Brenner, A. Damnjanovic, R. Sukhavasi, C. Patel, and S. Geirhofer, "Network Densification: The Dominant Theme for Wireless Evolution into 5G," *IEEE Communications Magazine*, vol. 52, pp. 82–89, 2014.

[3] M. Mirahsan, R. Schoenen, H. Yanikomeroglu, G. Senarath, and N. Dung-Dao, "User-in-the-loop for HetHetNets with backhaul capacity constraints," *IEEE Wireless Communications*, vol. 22, no. 5, pp. 50–57, 2015.

[4] R. Schoenen, H. U. Sokun, and H. Yanikomeroglu, "Effective quantum (eBit) tariff – A novel approach to enable smart data pricing," *IEEE Network Magazine, Special Issue on Smart Data Pricing*, August 2015.

[5] B. Zhang, Y. Li, D. Jin, P. Hui, and Z. Han, "Social-Aware Peer Discovery for D2D Communications Underlaying Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 1, pp. 177–190, 2015.

[6] L. Person and P. Gotsurve, "World LTE Market – Opportunities and Forecasts, 2012-2020," *Allied Market Research, Report IC 14144*, p. 107, April 2014.

[7] S. Jumisko-Pyykkö and T. Vainio, "Framing the context of use for mobile HCI," *International Journal of Mobile Human Computer Interaction, IGI Publishing Hershey, PA, USA*, vol. 2, pp. 1–28, October 2010.

[8] M. Nitti, R. Girau, and L. Atzori, "Trustworthiness Management in the Social Internet of Things," *IEEE Transactions on Knowledge and Data Engineering*, vol. 26, no. 5, pp. 1253–1266, 2014.

[9] L. Atzori, A. Iera, G. Morabito, and M. Nitti, "The Social Internet of Things (SIoT) – When social networks meet the Internet of Things: Concept, architecture and network characterization," *Computer Networks*, vol. 56, no. 16, pp. 3594–3608, 2012.

[10] L. Militano, A. Orsino, G. Araniti, A. Molinaro, and A. Iera, "A Constrained Coalition Formation Game for Multihop D2D Content Uploading," *IEEE Transactions on Wireless Communications*, 2015.

[11] A. Ometov, K. Zhidanov, S. Bezzateev, R. Florea, S. Andreev, and Y. Koucheryavy, "Securing Network-Assisted Direct Communication: The Case of Unreliable Cellular Connectivity," in *Proc. of IEEE Trustcom/BigDataSE/ISPA*, pp. 826–833, 2015.

[12] D. Brockmann, L. Hufnagel, and T. Geisel, "The scaling laws of human travel," *Nature*, vol. 439, pp. 462–465, 2006.

[13] D. Astely, E. Dahlman, G. Fodor, S. Parkvall, and J. Sachs, "LTE Release 12 and Beyond," *IEEE Communications Magazine*, vol. 51, no. 7, pp. 154–160, 2013.

[14] K. M. Alam, M. K. Saini, and A. El-Saddik, "Toward Social Internet of Vehicles: Concept, Architecture, and Applications," *IEEE Access*, vol. 3, pp. 343–357, 2015.

[15] A. Abrardo, G. Fodor, and B. Tola, "Network coding schemes for D2D communications based relaying for cellular coverage extension," *Transactions on Emerging Telecommunications Technologies*, 2015.