Enabling Cyber-Physical Communication in 5G Cellular Networks: Challenges, Solutions and Applications

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Outline

1. Introduction and Motivation
2. Solution 1: Offloading CPS onto Small Cells
    - Performance Metrics
    - Results
    - Conclusions
3. Solution 2: Offloading CPS onto D2D Links
    - RF Energy Harvesting Model for D2D
    - Energy Utilization Rate of D2D
    - Spectral Efficiency Analysis
    - Results
    - Conclusions
4. List of Publications

Introduction and Motivation

- We are facing an explosive increase in wireless data traffic
  - driven by the wide spread use of smartphones, tablets, sensors
  - CISCO estimated that over 50 billion sensors will be connected to the Internet by 2020 [1]
  - increasing popularity of online social networking applications
- This has generated a tsunami of information (big data)
- once this massive data is processed and analyzed, it can help
  - create new services and opportunities for both consumers and business alike

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[1] CISCO, "Fog computing and the internet of things: extend the cloud to where the things are," white paper, CISCO, Tech. Rep., 2015.

Introduction and Motivation

- Cyber-physical systems (CPS): a system with integrated communication and computational capabilities with tight interactions with the physical world [2]
  - Come CPS concepts: Machine type communications (MTC), Low power Wireless Personal Area Networks (LoWPAN), wireless sensor networks (WSN) and RFID
- CPS mainly consists of physical components and a cyber twin interconnected together
- Internet of Things (IoT) allows different CPS to be connected together for information transfer
- CPS are characterized by large amount of traffic with smart decision making

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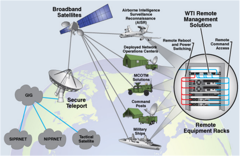
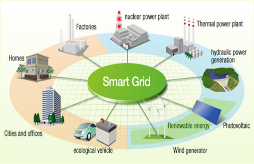
[2] B. Zheng, P. Deng, R. Anguluri, Q. Zhu and F. Pasqualetti, "Cross-Layer Codesign for Secure Cyber-Physical Systems," in IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol. 35, no. 5, pp. 699-711, May 2016.

CPS Applications

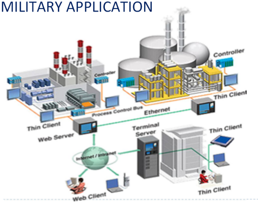
ENVIRONMENTAL MONITORING



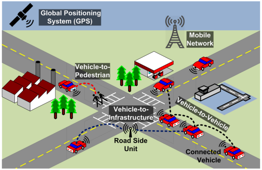
MILITARY APPLICATION



SMART GRIDS



FACTORY NETWORK



INTELLIGENT TRANSPORTATION SYSTEM

SMART CITY

Introduction and Motivation

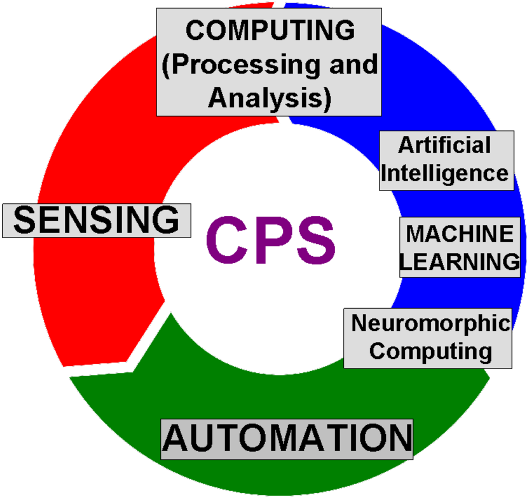


Figure 1: CPS cycle to automation.

Introduction and Motivation

- Cellular nets are appealing communication medium for CPS
  - can provide CPS communications with ubiquitous coverage, global connectivity, reliability and security
- It is not straightforward to enable CPS in cellular network
- Main challenges:
  - increased network congestion from massive number of devices
  - scarcity of cellular spectrum resources
  - generation of large amount of interference
- Some potential 5G technologies solutions:
  - device-to-device (D2D) communications
  - extreme densification
  - massive multi-input multiple output (MIMO) technologies
- In this work, we shed the light onto two potential 5G solutions
  - offloading CPS traffic onto D2D links
  - offloading CPS traffic onto small cells

Contributions

- We developed different solutions, schemes and systems of future 5G networks to help support the anticipated massive number of things
- Fundamental relationships between network performance and network parameters will be revealed
- Tractable analytical solutions using stochastic geometry tools for network performance demonstration and analysis verification

Thesis Statement

Thesis statement: By tuning specific network parameters such as offloading rate, spectrum partitioning, number of available channels, and so on, the proposed solutions allow the achievement of balance and fairness in spectral efficiency and minimum achievable throughout among cellular users and CPS devices

Stochastic Geometry

- Throughout our work, we use Stochastic Geometry
- It allows to model network topologies as a stochastic process Poisson point process (PPP)
- This provides an accurate model of interferers' spatial locations by averaging over all their potential topological realizations[3]

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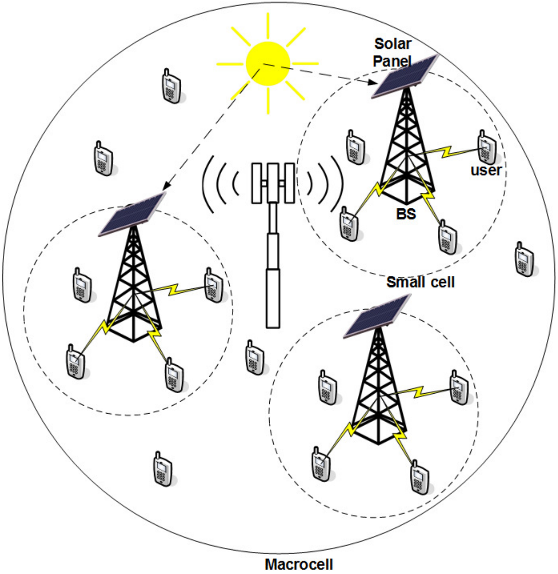
[3] H. ElSawy, E. Hossain, and M. Haenggi, "Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: A survey," IEEE Communications Surveys Tuto-rials, vol. 15, no. 3, pp. 996–1019, Third 2013.

Solution 1: Offloading CPS onto Small Cells
System Model

- We consider a single tier of power-grid macro base stations (MBSs) and K tiers of small cell base stations (SCBSs) powered by solar energy harvesting
- Part of the CPS communications will be offloaded to SCBSs to help relieve cellular congestion
- The uncertainty in energy harvesting can reduce the amount of offloaded data
- We try to answer several questions:
  - which network metrics maximize the amount of offloaded CPS traffic onto small cells?
  - How much gains can we obtain in the achievable throughput by offloading CPS traffic
  - how does the offloading impact the achievable throughput?

System Model



System Model

- A single tier (denoted by tier 0) of power-grid MBSs
  - locations form a homogeneous Poisson point process (HPPP) Φ_0 with density λ_0
- K tiers of solar energy harvesting SCBSs
  - locations form an HPPP Φ_k with density λ_k, where $k \in \{1, ..., K\}$
- A k^{th} tier BS transmits to each of its users with power P_k
- Cellular users are modeled by an HPPP Φ_{c} with intensity λ_{c}
- CPS devices are modeled by an HPPP Φ_{d} with intensity λ_{d}

System Model

- Each user connects to the BS with the highest received power
- We adopt a biased cell association policy
  - where each BS of tier k has biasing factor $B_k > 0$
- The service region $\mathcal{A}_k(x_k) \subset \mathbf{R}^2$ of the k^{th} tier BS located at $x_k \in \Phi_k$, with $k \in \{0, ..., K\}$:

$$\mathcal{A}_k(x_k) = \left\{ x \in \mathbf{R}^2 : x_k = \arg\max_{x \in x_j^\star} P_j B_j \|x - z\|^{-\alpha}, \right.$$
$$\left. \text{where } x_j^\star = \arg\max_{x \in \Phi_j^\star} P_j B_j \|x - z\|^{-\alpha} \right\},$$

  where $x_j^\star$ denotes the candidate BS with the highest average received signal power selected by user $z \in \Phi_\mathrm{u}$ as a serving BS

- We then obtain the average area of service region

Solar Energy Harvesting

- Powering SCBSs with solar power can help offset the costs of serving CPS devices
- Solar Energy Harvesting Challenges:
  - dependence on weather changing factors
  - geographical regions
  - inability to be used in cloudy areas that have low incidence of ambient solar irradiance
- We define the availability ρ_k of k^{th} tier SCBS as

$$\rho_k = \min\left(1, \frac{\epsilon_k}{P_{k,Tot}}\right). \tag{1}$$

  - $P_{k,\text{Tot}}$ is the total power consumption of k^{th} tier SCBS
  - ϵ_k is the harvested solar power of k^{th} tier SCBS
  - Thus, the density of available SCBSs forms a thinning PPP $\tilde{\Phi}_k$ from Φ_k, with intensity $\tilde{\lambda}_k = \rho_k \lambda_k$

CPS Offloading Rate

Lemma

The average number of CPS devices N_b^k that are offloaded from MBS b to SCBS k can be expressed as

$$\mathrm{E}\left[N_b^k\right] = \frac{\lambda_d}{\lambda_b} P_{c,k} \mathrm{E}[|A_k|]. \tag{2}$$

Theorem

The offloading rate of CPS devices from MBS b to SCBSs can be characterized as

$$\mu_b = \frac{\sum_{k=1}^{K} \mathrm{E}\left[N_b^k\right]}{\lambda_d / \lambda_b}. \tag{3}$$

Achievable Throughput

Lemma

By Shannon's theorem, the minimum achievable data rate of a typical user when it associates with a k^{th} tier SCBS can be expressed as

$$R_k = \frac{W}{\mathrm{E}\left[N_k\right]} \log_2\left(1+\beta\right), \tag{4}$$

where W is the system bandwidth; and $\mathrm{E}\left[N_k\right]$ is the average number of users associated with k^{th} tier SCBS, and given as
$\mathrm{E}\left[N_k\right] = \lambda_u/\tilde{\lambda}_k + \mathrm{E}\left[N_b^k\right]$.

Achievable Throughput

Theorem

The minimum achievable throughput of all K-tiers small cells can be characterized as

$$R_{total} = \sum_{k=1}^{K} P_{c,k} \lambda_u \mathrm{E}[|A_k|] R_k \tag{5}$$

Eq. (5) shows that the minimum achievable throughput is related to the availabilities of SCBSs, the users density, the number of users offloaded to SCBSs and the coverage probability

Similarly, we characterize the minimum achievable throughput of the 0-tier MBSs

Simulation Parameters

Unless otherwise noted, we set the following system parameters:

$\lambda_{\mathsf{u}} = 100/(\pi 1000^2)$;
$\lambda_k = [0.09, 0.05, 0.01] \cdot \lambda_{\mathsf{u}}$;
$\beta = 3$ dB;
$\lambda_{\mathsf{d}} = 0.5\lambda_{\mathsf{u}}$;
$W = 20 * 10^6$ Hz;
$P_k = [46, 33, 23]$ dBm;
$B_k = [1, 10, 10]$ dB;
$\alpha = 4$;
$K = 3$.

Results

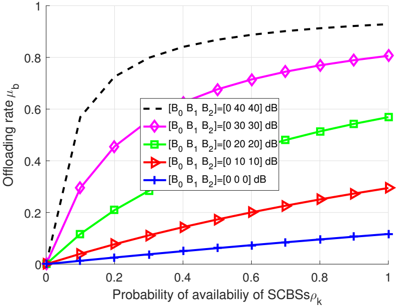


Figure 2: As the biasing factor increases, so does the offloading rate since CPS devices become more inclined towards associating with SCBSs

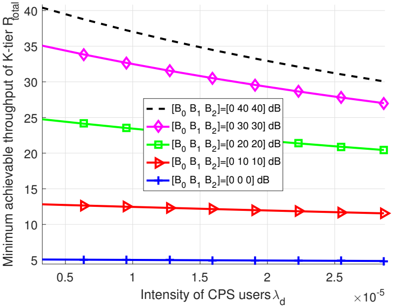


Figure 3: as the biasing factor increases, the total throughput of users increases, since more users get offloaded from macrocell to small cells

Results

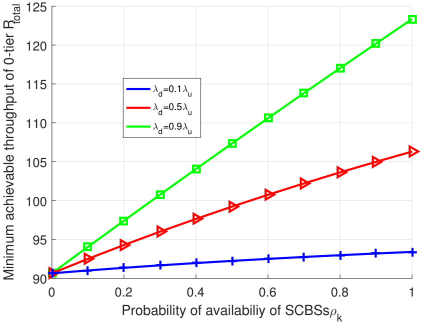


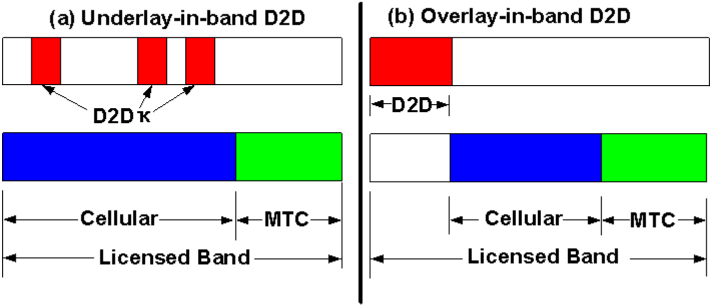
Figure 4: when SCBSs become more available, the macrocell experiences higher throughput since more CPS users get offloaded to SCBSs

Conclusions

- We have presented a potential solution to the anticipated massive number of CPS devices
    - using the concept of cell shrinking and offloading technology
- We allowed SCBSs to be powered by solar power to offset the costs of serving CPS devices
- We showed that as long as SCBSs are available, the CPS traffic offloading can bring benefits to both macrocell BSs and SCBSs

Solution 2: Offloading CPS onto D2D Links
System Model

- Offloading CPS traffic onto D2D links requires D2D users to use their own limited energy to relay
- Exploit RF energy harvesting for powering D2D relay transmissions
- We consider an uplink cellular network
  - D2D and cellular users share the licensed uplink spectrum
  - MTC devices use orthogonal spectrum resources



Solution 2: Offloading CPS onto D2D Links
System Model

- We face a fundamental trade-off:
  - i) Reducing the spectrum partition factor
    - protects cellular users from underlaid D2D transmissions
    - BUT reduces the probability that users operate in D2D mode [4]
  - ii) BUT increases the amount of time that users can spend harvesting energy to support relaying MTC traffic
  - Therefore, the spectrum partition factor should be set
    - small enough to simultaneously manage interference to cellular users
    - to ensure users harvest sufficient energy for relaying
    - but not so small that too few users operate in D2D mode
- We study this trade-off analytically using tools from stochastic geometry

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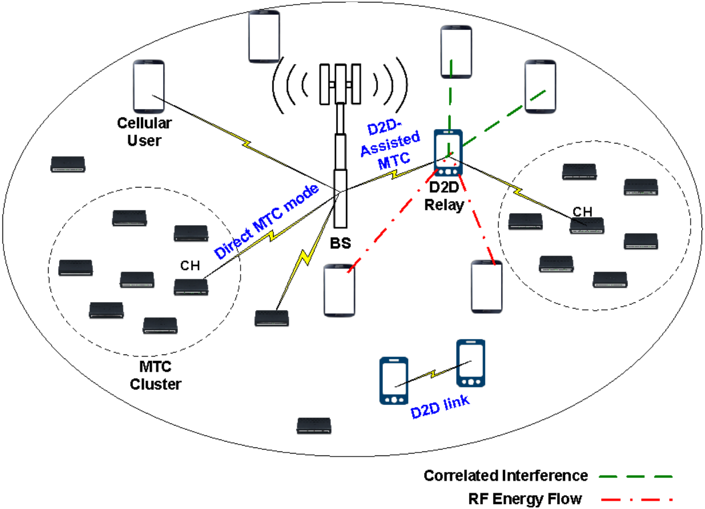
[4] Lin, Xingqin, Jeffrey G. Andrews, and Amitava Ghosh. "Spectrum sharing for device-to-device communication in cellular networks." IEEE Transactions on Wireless Communications 13.12 (2014): 6727-6740.

Solution 2: Offloading CPS onto D2D Links
System Model



System Model

- Denote $\mathcal{A}(k, R_{\mathrm{B}})$ as the coverage region of a macrocell [5].
- MTC devices are modeled by an independent HPPP, Φ_{M} with intensity λ_{M}
- We differentiate between three different types of users:
  - **D2D Transmitter:** (Φ_D with intensity λ_D) if SINR $> \theta_D$
  - **Cellular user:** (Φ_C with intensity λ_C) when user cannot operate in D2D mode

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[5] Novlan, Thomas D., Harpreet S. Dhillon, and Jeffrey G. Andrews. "Analytical modeling of uplink cellular networks." IEEE Transactions on Wireless Communications 12.6 (2013): 2669-2679.

System Model

- **MTC device:** MTC CH (MTCCH) can use two different modes for transmission of the collected packet from its cluster members as follows:
  - *D2D-assisted MTC mode:*
    - There is a D2D relay available in the vicinity of the MTCCH
    - and the end-to-end SINR using a D2D relay is $> \theta_{\mathrm{M}}$
  - *Direct MTC mode:*
    - There is no available D2D relay to provide services to the MTCCH;
    - however the end-to-end SINR ratio of the direct link between MTCCH and the BS is $> \theta_{\mathrm{M}}$

System Model Assumptions

- $|B|$ (set cardinality) is the number of channels
- D2D transmitters can access $\kappa|B|$ of them randomly
  - $\kappa \in [0, 1]$ measures the fraction of spectrum available to D2D users [6]
- The D2D transmit power P_D is split among the $\kappa|B|$ subchannels as
  - $\hat{P}_D = (1/(\kappa|B|))P_D$
- The distance between any two nodes i and j: $d(i, j)$
- The power of UEs' signal decays at a rate of $l(i, j) = d(i, j)^{-\alpha}$
  - $\alpha > 2$ is the path-loss exponent
- Rayleigh fading with mean one models the small-scale fading
  - $h_{i,j}$ denoting the channel coefficient between nodes i and j

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[6] X. Lin, J. G. Andrews and A. Ghosh, "Spectrum Sharing for Device-to-Device Communication in Cellular Networks," in IEEE Transactions on Wireless Communications, vol. 13, no. 12, pp. 6727-6740, Dec. 2014.

System Model Assumptions

- We are only interested in cellular transmitters that are not using $\kappa|B|$ subchannels
  - since D2D users cannot use $\kappa|B|$ subchannels for harvesting energy and transmitting information simultaneously to simplify the system operation and analysis
- $\tilde{\Phi}_C$ is a PP representing the set of CUs not using $\kappa|B|$ subchannels

RF Energy Harvesting Model for D2D

- Each D2D user is equipped with an RF power conversion circuit
- The cellular uplink RF interference samples received by D2D user inside $\mathcal{A}$ and outside of it can be expressed as:

$$y[n] = \sum_{i \in \tilde{\phi}_C} s_i[n] + z[n], \tag{6}$$

- $n = 0, 1, ..., N - 1$ is the sample index (N total number of samples)
- $s_i[n] = (P_C h_{i0} l(i,0))\,[n]$ is the nth sample of the received signal from cellular transmitter i by a typical D2D user
- $z[n]$ is the Gaussian noise ($z[n] \sim \mathcal{N}(0, \sigma_n^2)$)

RF Energy Harvesting Model for D2D

- The average received power can be expressed as $\xi = 1/N \sum_{n=0}^{N-1} y[n]$
- When N is large, by central limit theorem, $\xi \sim$ Gaussian distribution
- Thus, we can characterize the mean and variance of ξ as [7]:

$$\begin{aligned} \mathrm{E}(\xi) &= \sum_{i \in \tilde{\phi}_C} P_C h_{i0} l(i,0) = I_{\mathrm{RF}}, \\ Var(\xi) &= \frac{1}{N^2}\left(I_{\mathrm{RF}} + \sigma_n^2\right), \end{aligned} \tag{7}$$

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[7] X. Kang, Y. C. Liang, H. Garg, and L. Zhang, "Sensing-based spectrum sharing in cognitive radio networks," IEEE Transactions on Vehicular Technology, vol. 58, no. 8, pp. 4649–4654, Oct 2009.

RF Energy Harvesting Model for D2D

We can express the expected RF energy harvesting rate η as:

$$\eta = \lambda_D \int_0^{\infty} f_{I_{\mathrm{RF}}}(x) \mathcal{P}\left(\xi > 0 | I_{\mathrm{RF}}\right) dx \tag{8}$$

- $f_{I_{\mathrm{RF}}}(x)$ is the PDF of I_{RF}; and $\mathcal{P}\left(\xi > 0 | I_{\mathrm{RF}}\right) = Q\left(\frac{-Nx}{\sqrt{x+\sigma_n^2}}\right)$

Theorem

The expected RF energy harvesting rate is expressed as:

$$\eta = \frac{\pi^{3/2} \upsilon_e \sqrt{P_C} \tilde{\lambda}_C \lambda_D}{4} \int_0^{\infty} Q\left(\frac{-Nx}{\sqrt{x+\sigma_n^2}}\right) x^{-3/2} e^{-\frac{\pi^4 \tilde{\lambda}_C^2 P_C}{16x}} dx. \tag{9}$$

Energy Utilization Rate

- Energy utilization rate υ: number of energy units required per second by a D2D user: [8]

$$\upsilon = \kappa \lambda_D \exp \left(-\lambda_D \pi \left(\frac{\hat{P}_D}{\epsilon} \right)^{2/\alpha} \Gamma \left(1 + \frac{2}{\alpha} \right) \right) \qquad (10)$$

  - Obtained by calculating the area of transmission region of D2D user
  - Transmission region: range within which other nodes can receive D2D signal with a power above a specified decoding threshold ϵ
- Assuming infinite battery capacity and using calculations in [9]
- we can express the transmission probability of D2D user as:

$$\rho = \min \left(1, \frac{\eta}{\upsilon} \right) \qquad (11)$$

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[8] H. S. Dhillon, Y. Li, P. Nuggehalli, Z. Pi, and J. G. Andrews, "Fundamentals of heterogeneous cellular networks with energy harvesting," IEEE Transactions on Wireless Communications, vol. 13, no. 5, pp. 2782–2797, May 2014.

[9] K. Huang, "Spatial throughput of mobile ad hoc networks powered by energy harvesting," IEEE Transactions on Information Theory, vol. 59, no. 11, pp. 7597–7612, Nov 2013.

Cellular spectral efficiency

- We adopt the spatial Aloha access scheme for MTC devices
  - The device transmits with probability ϖ in each time slot
  - refrains from transmission with probability $1-\varpi$
- The effective cochannel MTC interferers form a thinning HPPP $\tilde{\Phi}_{\mathrm{M}}$ from Φ_{M} with intensity $\tilde{\lambda}_{\mathrm{M}} = \varpi\lambda_{\mathrm{M}}$
- The aggregate interference at a typical BS comes from cellular transmitters in other cells; D2D transmitters and MTC devices in all cells
- It can be expressed as

$$I_{\mathrm{BS}} = \sum_{k\in\Phi_{\mathrm{C}}\cap\mathcal{A}^c} P_{\mathrm{C}} h_{k0} l(k,0) + \sum_{k\in\tilde{\Phi}_{\mathrm{D}}} \hat{P}_{\mathrm{D}} h_{k0} l(k,0) + \sum_{k\in\tilde{\Phi}_{\mathrm{M}}} P_{\mathrm{M}} h_{k0} l(k,0). \tag{12}$$

Theorem

The spatially averaged spectral efficiency of the cellular transmitters, R_C, can be characterized as

$$R_C = \frac{343\sqrt{7}\lambda_B^{7/2}}{20\sqrt{2}\lambda_C}\left[\left(\frac{7\lambda_B}{2}\right)^{-5/2} - \left(\frac{7\lambda_B}{2} + \lambda_C\right)^{-5/2}\right] \cdot \int_{r>0} 2\pi r \lambda_B e^{-\pi\lambda_B r^2} \int_{t>0} e^{-\sigma_n^2 r^\alpha (2^t - 1)} \mathcal{L}_{I_{BS}}\left(r^\alpha\left(2^t - 1\right)\right) dt dr \tag{13}$$

D2D-Assisted MTC Link

- Cooperation introduces a correlation in the aggregate interference
  - due to receivers being closely located to each other
- Both source node s and relay node r work in time division duplex
- The aggregated interference at the relay node r during time slot t:

$$I_r^t = \sum_{j \in \Phi_{\mathrm{C}}^t \cap \mathcal{A}} P_{\mathrm{C}} h_{jr} l(j,r) + \sum_{j \in \Phi_{\mathrm{C}}^t \cap \mathcal{A}^c} P_{\mathrm{C}} h_{jr} l(j,r) + \sum_{j \in \tilde{\Phi}_{\mathrm{D}}^t \setminus \{s\}} \hat{P}_{\mathrm{D}} h_{jr} l(j,r).$$

Similarly, the aggregated interference at the destination node d:

$$I_d^t = \sum_{j \in \Phi_{\mathrm{C}}^t \cap \mathcal{A}^c} P_{\mathrm{C}} h_{jd} l(j,d) + \sum_{j \in \tilde{\Phi}_{\mathrm{D}}^t \setminus \{s\}} \hat{P}_{\mathrm{D}} h_{jd} l(j,d) + \sum_{j \in \tilde{\Phi}_{\mathrm{M}}^t \setminus \{s\}} P_{\mathrm{M}} h_{jd} l(j,d)$$

- Channel SIR between source and relay is: $\gamma_{s,r} = P_{\mathrm{M}} h_{sr} l(s,r) / I_r^t$
- Channel SIR between relay and destination: $\gamma_{r,d} = \hat{P}_{\mathrm{D}} h_{rd} l(r,d) / I_d^t$

D2D-Assisted MTC Link

The spatially averaged spectral efficiency of the D2D-assisted MTC links, R_{M}^{r}, can be characterized as

$$R_{\mathrm{M}}^{r} \approx$$

$$\varpi \int_{0}^{\infty} \left[\exp\left(-\lambda_{\mathrm{C}} \int_{R_{\mathrm{B}}}^{\infty} 1 - \frac{1}{T_1(x,t)\, T_2(x,t)} dx \right) \exp\left(-\tilde{\lambda}_{\mathrm{D}} \int_{0}^{\infty} 1 - \frac{1}{T_1(x,t)\, T_2(x,t)} dx \right) \right.$$

$$\left. \exp\left(-\lambda_{\mathrm{C}} \int_{0}^{R_{\mathrm{B}}} 1 - \frac{1}{T_2(x,t)} dx \right) \exp\left(-\tilde{\lambda}_{\mathrm{M}} \int_{0}^{\infty} 1 - \frac{1}{T_1(x,t)} dx \right) \right] dt,$$

where $T_1(x,t) = 1 + \left((2^t - 1) I(x,d) \hat{P}_{\mathrm{D}}^{-1} \right)^{2/\alpha} 4\pi\mu^2/9$;

$T_2(x,t) = \prod_{n=1}^{N_{\mathrm{r}}} \left(1 + \left((2^t - 1) I(x,n) P_{\mathrm{M}}^{-1} \right)^{2/\alpha} \mathrm{E}[\|s - r\|]^2 \right)$.

Results

Radius of the macrocell R_B	788 meters
Density of macrocells λ_B	$1/\left(\pi R_\mathsf{B}^2\right)$
Density of UEs λ_U	$10\lambda_\mathsf{B}$
Density of MTC devices λ_M	$2\lambda_\mathsf{D}$
Power of a cellular user P_C	200 mW
Power of D2D users, $\hat{P}_\mathsf{D}$, and MTC devices, P_M	2 mW
The total number of samples N	5000
Radius of relay-assisted region R_r	100 meters
Target SINR threshold θ_D, θ_C, θ_M	10 dB
Total number of available channels $\|B\|$	10
Spectrum partition factor κ	0.5
Aloha access probability ϖ for MTC devices	0.5
Path-loss exponent α	4
RF energy conversion efficiency υ_e	0.6

Results

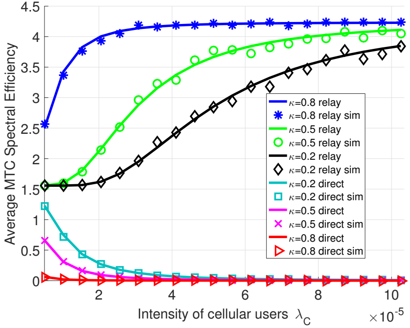

Figure 5: The average MTC spectral efficiency in terms of λ_C for different values of κ ($\lambda_D = 10\lambda_B$).

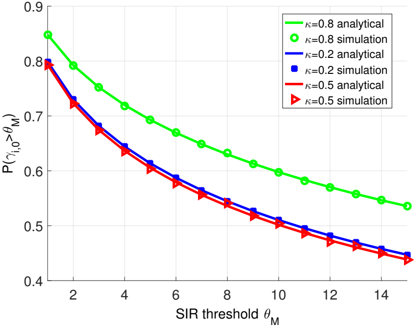

Figure 6: MTC coverage probability in terms of θ_M for different κ.

Results

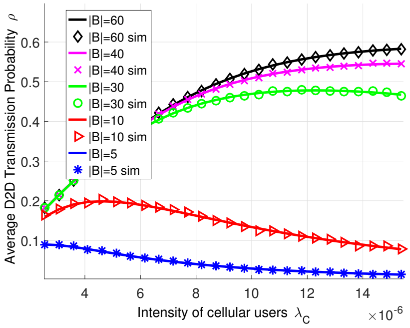

Figure 7: The average D2D transmission probability ρ in terms of λ_C for different values of $|B|$ ($\kappa = 0.1$).

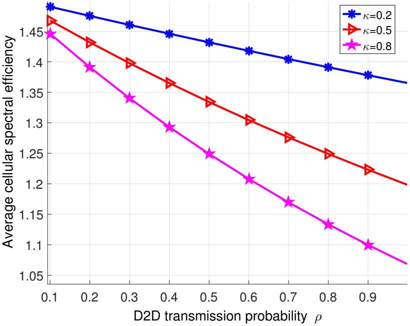

Figure 8: The average cellular spectral efficiency, R_C, in terms of transmission probability, ρ, for different values of κ.

Results

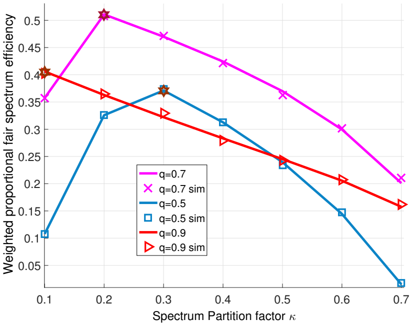

Figure 9: The weighted proportional-fairness spectral efficiency versus κ for different values of q ($\lambda_{\mathrm{D}} = 10\lambda_{\mathrm{B}}$; $w_C = 0.65$).

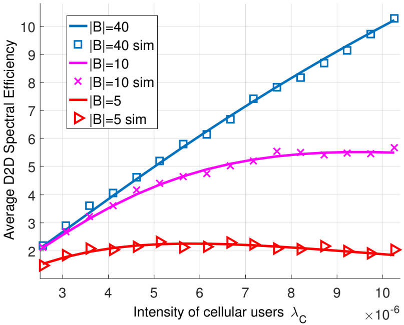

Figure 10: The average D2D spectral efficiency in terms of λ_{C} for different values of $|B|$.

Conclusions

- Results have shown that
  - a small spectrum partition factor κ ($\kappa = 0.2$ or $\kappa = 0.3$ when 70% or 50% of UEs operate in D2D mode, respectively)
  - combined with an adequate number of available channels in the network ($|B| = 30$ to 40) can achieve
    - i) a balance and fairness in weighted spectral efficiency among D2D and cellular users that are sharing the spectrum
    - ii) a higher D2D transmission probability
    - iii) a relatively high MTC and D2D spectral efficiency in a dense cellular environment

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