Evolution Toward 5G Cellular Networks: A Radio Resource and Interference Management Perspective

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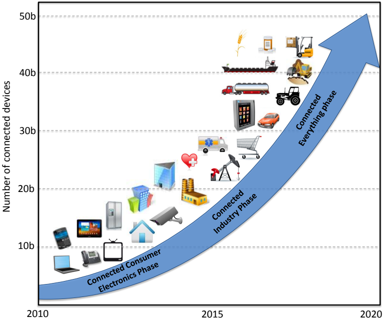
Outline

- Part I: Visions and requirements for 5G cellular networks
- Part II: Enabling technologies for 5G
- Part III: Interference management challenges in 5G multi-tier networks
- Part IV: Tier-aware downlink resource allocation in multi-tier OFDMA networks
- Part V: Distributed cell association and power control schemes in multi-tier networks
- Part VI: Cognitive spectrum access by small cells
- Part VII: Mode selection and power control for underlay D2D communication

- Part I: Visions and requirements for 5G cellular networks

Visions and requirements for 5G

- Exponential increase of the population of wireless devices with ubiquitous Internet connectivity (which is expected to reach 50 billion by 2020)
- Mobile cloud-based services and “big data” analytics
- Evolution phases: connected consumer electronics phase, connected industry phase, and connected everything (IoT) phase



Visions and requirements for 5G

- Human-centric as well as connected machine-centric networks will need to be enabled.
- Enable any mobile application and service to connect to anything at anytime (physical things, processes, etc.) in a timely and flexible manner.
- Near instantaneous "zero distance" connectivity between connected people and connected machines
- Exisiting wireless systems will not be able to deal with thousand fold increase in mobile braodband data.
- 5G: the next generation of ubiquitous ultra-broadband network

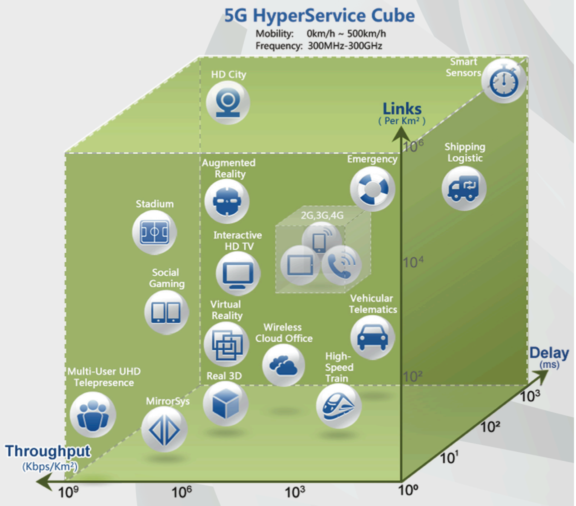
Source: "5G: A technology vision", Huawei

Visions and requirements for 5G

- 5G technologies are expected to support
  1. **Massive capacity** and **massive connectivity**
  2. Increasingly diverse set of services, applications, and users with extremely diverging requirements
  3. 1000 times higher mobile data volume per unit area (1000$\times$ challenge)
  4. 10-100 times higher number of connecting devices and user data rate (e.g., peak data rate of 10 Gbps for low mobility and peak data rate of 1 Gbps for high mobility)
  5. Less than 1 ms latency to support real-time control applications
  6. Max 10 ms switching time between different radio access technologies (RATs)
  7. Communication scenarios in the range of 350 - 500 km/hr (compared to 250 km/hr in 4G networks)
  8. 10 times longer battery life

Visions and requirements for 5G

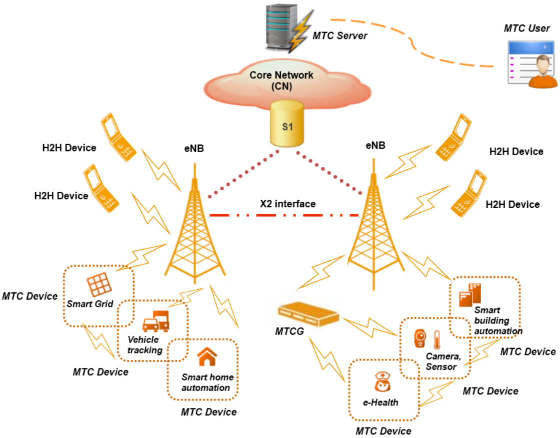
- 5G service scenarios and requirements



Source: "5G: A technology vision", Huawei

- Native support for Machine-type communication (MTC)
  1. Massive number of connected devices (e.g., smart metring devices, sensors)
  2. Data size of each transmission is small
  3. Very high link reliability, low latency and real-time operation
  4. May require radical changes at both the node and architecture levels

MTC in LTE-A networks:



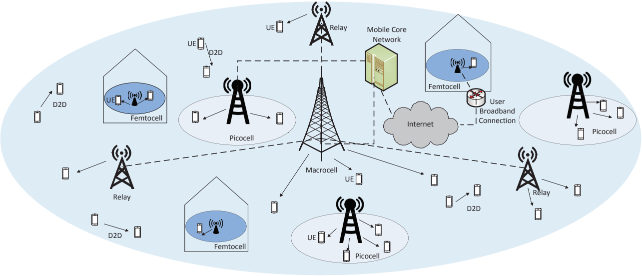
M. Hasan, E. Hossain, and D. Niyato, "Random access for machine-to-machine communication in LTE-Advanced networks: Issues and approaches," *IEEE Communications Magazine*, Special Issue on "Smart Cities", vol. 51, no. 6, June 2013.

Visions and requirements for 5G

- 5G technologies are expected to support

  1. Architectural enhancement: mixture of network tiers of different sizes, transmit powers, backhaul connections, different RATs (GSM, HSPA+, LTE, LTE-Advanced and beyond LTE-Advanced)
  2. **BS densification**: relays, picocells, femtocells
  3. Low-powered radio access nodes (small cells) which can operate in licensed and/or unlicensed spectrum bands and have a transmission range of several tens to several hundreds of meters
  4. Millimeter-wave communication: 30-300 GHz bands
  5. Advanced physical communications technology: high-order spatial multiplexing MIMO (distributed antenna systems and massive MIMO, spatial modulation)
  6. New system concepts to boost spectral and energy efficiency (e.g., traditional methods for radio resource and interferece management [RRIM] in single and two-tier networks may not be efficient)

A multi-tier cellular network architecture:



E. Hossain, M. Rasti, H. Tabassum, and A. Abdelnasser, "Evolution towards 5G multi-tier cellular wireless networks: An interference management perspective," *IEEE Wireless Communicatons*, to appear, 2014. Available: [Online] http://arxiv.org/abs/1401.5530

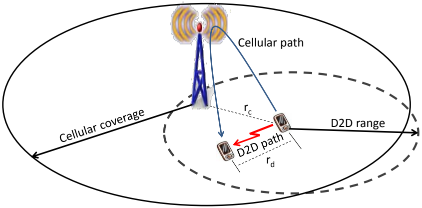
Visions and requirements for 5G

- 5G technologies are expected to support
  1. Flexible and efficient use of all available non-contiguous spectrum for different network deployment scenarios
  2. Utilization of any spectrum and any access technology for the best delivery of services
  3. On-demand customization of mobile network technologies that better ensure QoS, increase network TVO (Total Value of Opportunity), decrease network TCO (Total Cost of Ownership), and reduce energy consumption
  4. New types of network deployments, including ultra-dense radio networking with self-backhauling, device-to-device communication, dynamic spectrum refarming and radio access infrastructure sharing.

"5G: A technology vision", Huawei

Visions and requirements for 5G

- Device-to-device (D2D) communication
  1. D2D communication (already being studied in 3GPP as a 4G add-on) should be natively supported in 5G as another cell-tier.
  2. Permits transmitter-receiver pairs coexisting in close proximity to establish direct peer-to-peer connections without the use of BSs (social networking, peer-to-peer content sharing, public safety communications)
  3. Enables short-range, low-power links to coexist with cellular links (improves spectral efficiency, decreases power consumptions of UEs, improves total network throughput)
  4. Dense spectrum reuse, irregular interference topology
  5. Spectrum overlay or spectrum underlay



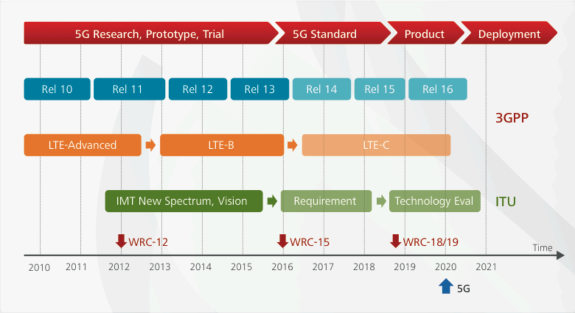
Visions and requirements for 5G

- Necessary breakthroughs
  1. Multiple access/interference management and advanced waveform technologies combined with advances in coding and modulation algorithms (for massive IoT connectivity)
  2. Miniaturized multi-antenna technologies and significantly advanced baseband and RF architecture (e.g., for massive MIMO computations)
  3. Advanced RF domain processing, single-frequency full-duplex radio technologies
  4. Device technologies to support a vast range of capabilities
  5. Backhaul design for ultra dense networking
  6. Virtualized and cloud-based radio access infrastructure

"5G: A technology vision", Huawei

Visions and requirements for 5G

- 5G roadmap and timeline
  1. 5G is in its early research stages.
  2. New IMT spectrum expected to be agreed upon during World Radio Communication Conference (WRC) in 2015



"5G: A technology vision", Huawei

- Part II: Enabling technologies for 5G networks

- BS densification: relays, picocells, femtocells
  1. Outdoor small cells deployed by operators, i.e., picocells
  2. Macro and small cells connected to each other via ideal or non-ideal backhaul (cloud-RAN and wireless backhaul architecture)
  3. At locations without wired backhaul access, relay nodes can be deployed
  4. Mobile small cells (e.g., mobile femtocells inside vehicles)

Enabling technologies for 5G

- Small cells include **femtocells**, **picocells**, **microcells**, and **metrocells**.
- Small cells can support wireless applications for homes and enterprises as well as metropolitan and rural public spaces.
- **Heterogeneous networks (HetNets)/Small cell networks** including macrocells and small cells of all types will provide improved spectrum efficiency (bps/Hz/km^2), capacity, and coverage.
- In a HetNet, small cells are traffic offloading spots in the radio access network to decrease the congestion in macrocells, and enhance the users' QoS experience.
- Small cells in the licensed bands can be used in the cellular networks standardized by 3GPP, 3GPP2, and WiMAX forum.

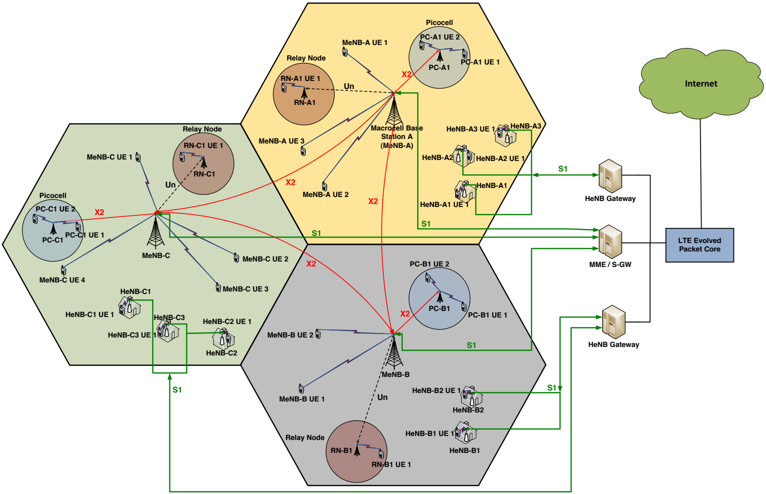
Enabling technologies for 5G

Attribute	MeNB	Picocell	HeNB	Wi-Fi
Coverage	Wide area	Hot spot	Hot spot	Hot spot
Type of coverage	Outdoor	Outdoor, indoor	Indoor	Indoor
Density	Low	High	High	High
BS installation	Operator	Operator	Subscriber	Customer
Site acquisition	Operator	Operator	Subscriber	Customer
Tx. range	300-2000m	40-100m	10-30m	100-200m
Tx. power	40W (approx.)	200mW-2W	10-100mW	100-200mW
Band license	Licensed	Licensed	Licensed	Unlicensed
System bandwidth	5, 10, 15, 20MHz (upto 100MHz)	5, 10, 15, 20MHz (upto 100MHz)	5, 10, 15, 20MHz (upto 100MHz)	5, 10, 20MHz
Tx. rate	upto 1Gbps	upto 300Mbps	100Mbps-1Gbps	upto 600Mbps
Cost (approx.)	$60,000/yr	$10,000/yr	$200/yr	$100-200/yr
Power consump.	High	Moderate	Low	Low
Backhaul	S1 interface	X2 interface	IP	IP
Mobility	Seamless	Nomadic	Nomadic	Nomadic
QoS	High	High	High	Best-effort

- Different types of small cells
  1. **Femtocell**: small area covered by a small base station, called the femto access point (FAP), intended for residential indoor applications, installed and managed by the customers
  2. **Key attributes**: IP backhaul, self-optimization, low power consumption, ease of deployment (user-deployed), closed/open/hybrid access
  3. **Picocell**: low-power compact base stations, used in enterprise or public indoor areas, encompasses outdoor small cells as well
  4. **Key attributes**: wired or wireless backhaul, operator deployed, self-optimization, open access

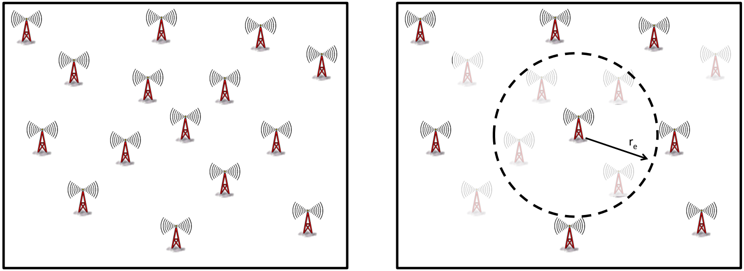
- Different types of small cells
  1. **Microcell**: outdoor short-range base station aiming at enhancing coverage for both indoor and outdoor users
  2. **Key attributes**: wired or wireless backhaul, self-optimization, low power consumption, open access
  3. **Metrocell**: small cell technologies designed for high-capacity metropolitan areas, typically installed on building walls, lampposts; can include technologies such as femtocells, picocells, and microcells
  4. **Key attributes**: wired or wireless backhaul, operator deployed, self-optimization, open access
  5. **Relays**: operator deployed, open access, wireless backhaul

- LTE/LTE-A-based small cell network architecture



- Cognitive small cells
  1. Due to their limited coverage, small cells may have unplanned deployment with high densities (hence complete centralized control may be infeasible).
  2. Small cells need to have the Self-Organizing Network (SON) capabilities (through **cognition**) for efficient operation with limited centralized control.
  3. Cognitive **small cell base stations (SBSs)** will be capable of monitoring the surrounding environment, locate major interference sources, and avoid them by opportunistically accessing the orthogonal channels.
  4. To be robust and adaptive to topological changes, the design parameters (e.g., spectrum sensing threshold) for cognitive SBSs should be independent from the topology and account for the topological randomness.

- Cognitive small cells
  1. Each network element performs spectrum sensing to access the spectrum.
  2. Cognitive spectrum access affects the locations and density of interferers.

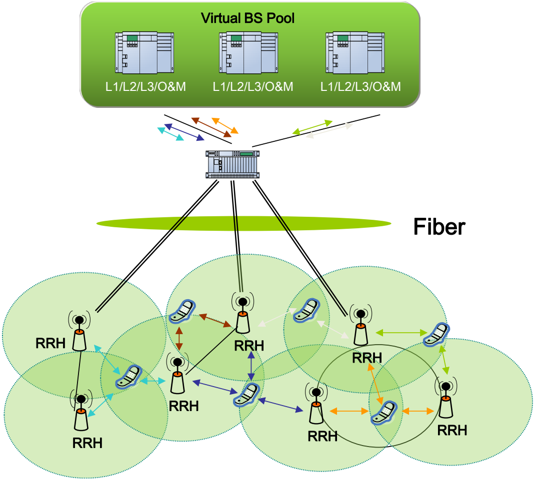


Enabling technologies for 5G

- Cloud-RAN (C-RAN) architecture
  1. Baseband signals from several hundred cells received and processed at a server platform
  2. Distributed radio units (i.e., RRHs) plus antennas located at the remote site
  3. High-bandwidth low-latency optical transport network connects RRHs and BBU (Baseband Unit) pool
  4. BBU is composed of high-performance programmable processors and real-time virtualization technology
  5. Typically favored by operators with access to optical fiber and/or extremely high-density scenarios

- C-RAN architecture
  1. Simplifies implementation of LTE-Advanced features such as coordinated multipoint (CoMP) and enhanced intercell interference coordination (eICIC)
  2. Real-time low-latency virtualization provides a pool of resources that can be dynamically allocated for baseband processing
  3. Install new RRHs and connect them to the BBU pool to expand network coverage or split the cell to improve capacity.
  4. Joint processing and demodulation of multiple users' signals
  5. Joint resource allocation among multiple RATs
  6. "Fully-centralized" vs. "semi-centralized" C-RAN architecture

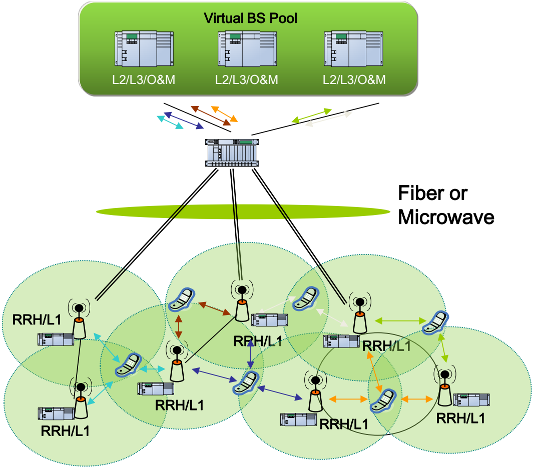
- A centralized C-RAN architecture



Source: "C-RAN: The road towards Green RAN", White Paper, Version 2.5 (Oct. 2011), China Mobile Research Institute

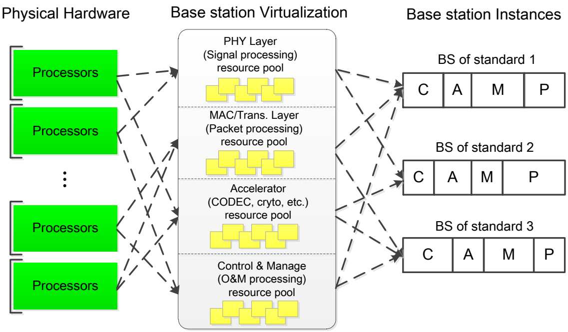
Enabling technologies for 5G

- A semi-centralized C-RAN architecture



Source: "C-RAN: The road towards Green RAN", White Paper, Version 2.5 (Oct. 2011), China Mobile Research Institute

- Baseband pool in centralized C-RAN architecture



Source: "C-RAN: The road towards Green RAN", White Paper, Version 2.5 (Oct. 2011), China Mobile Research Institute

- Fully-centralized C-RAN architecture
  1. Easy upgrading and network capacity exapnsion
  2. Better capability of supporting multi-standard operation
  3. Maximum resource sharing
  4. Better support for multi-cell collaborative signal processing
  5. Easier to develop and deploy software-defined radio to upgrade air interface standards
  6. High bandwidth requirement between BBU and RRHs (to carry basebnad signal)

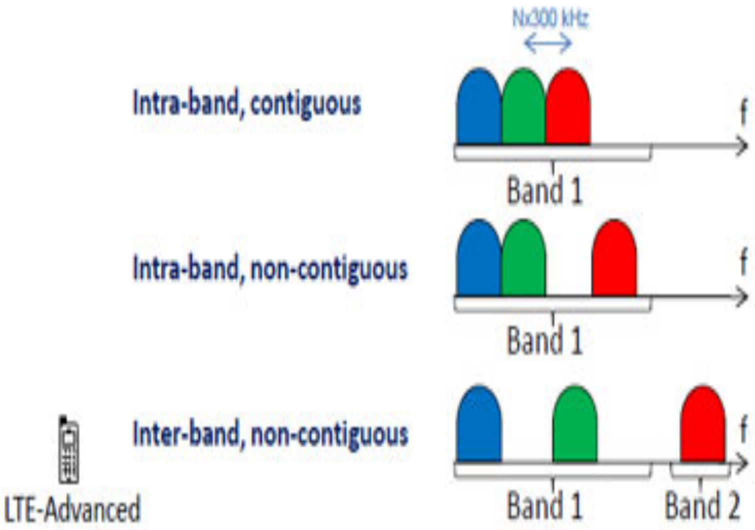
- Semi-centralized C-RAN architecture

  1. Separates the baseband processing from BBU and integrates with RRH
  2. Much lower transmission bandwidth between BBU and RRH (the BBU-RRH connection only needs to carry demodulated data)
  3. Since baseband processing is integrated into RRH, less flexibility in upgrading and multi-cell collaborative signal processing

Enabling technologies for 5G

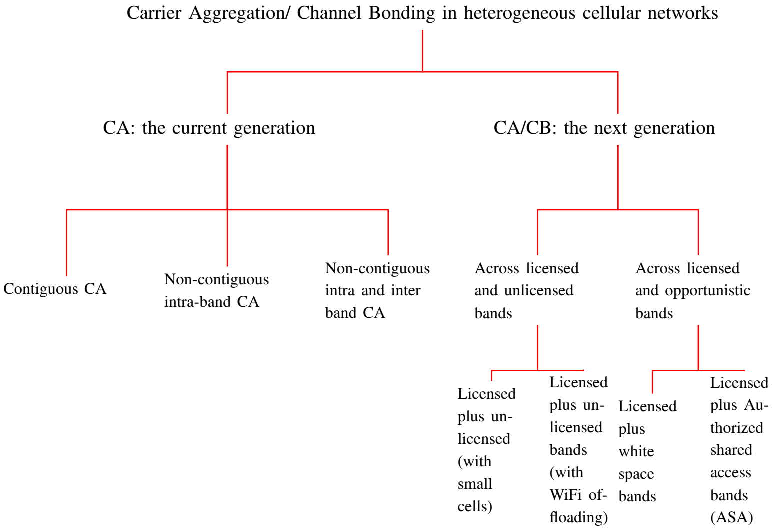
- Carrier aggregation (CA)/carrier bonding (CB)
  1. Introduced in LTE release-10: multiple LTE carriers, also called component carrier (each with bandwidth upto 20 MHz) can be used in parallel for transmission or reception
  2. Entire set of aggregated carriers can be seen as a single RF carrier
  3. Intra-band aggregation with frequency-contiguous component carriers
  4. Intra-band aggregation with non-contiguous component carriers
  5. Inter-band aggregation with non-contiguous component carriers
  6. CB used in unlicensed bands by WiFi networks to combine adjacent channels (e.g., in 2.4 GHz and 5 GHz)

- Carrier aggregation in LTE-A (source: 3GPP website)



- CA/CB in licensed, unlicensed, and opportunistic spectrum access (OSA) bands
    1. Techniques designed for conventional CA in the licensed bands cannot be directly applied for CA in unlicensed and OSA bands (e.g., TV white space between 50 MHz and 700 MHz, authorized shared access [ASA] bands between 2.3-2.4 GHz)
    2. ASA allows operators to access the underutilized spectrum on a shared basis without interfering with incumbent spectrum holders.
    3. White space spectrum has excellent propagation characteristics while ASA bands are mostly suitable for local area coverage (e.g., for small cells)
    4. Multiple independent operators can decide to combine channels simultaneously in the licensed, unlicensed, and OSA bands.

- CA/CB in 5G heterogeneous networks



Enabling technologies for 5G

- CA/CB in 5G heterogeneous networks
  1. CA first deployed in HSPA networks to support only contiguous intra-band aggregation of two carriers
  2. LTA-A allows CA of contiguous and non-contiguous carriers within both intra and inter-spectrum bands (up to 100 MHz).
  3. Performed centrally, same operator, licensed bands only
  4. In 5G, extend the concept of CA in unlicensed and OSA bands using a unified cellular network.
  5. In 2.4 GHz, only three 20 MHz channels are non-overlpping whereas 5 GHz has up to 500 MHz of spectrum (more than 20 non-overlapping channels of 20 MHz bandwidth)
  6. Signaling information is always communicated in the licended bands ("anchoring in the licensed spectrum")
  7. A user's primary component carrier (PCC) in the licensed band is aggregated with secondary component carriers (SCCs) in the unlicensed band.

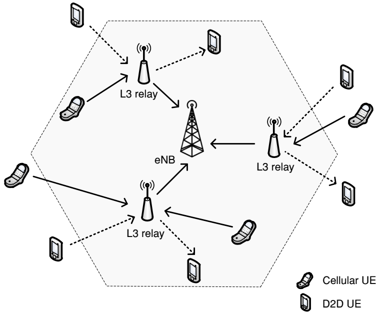
Enabling technologies for 5G

- Around 600 MHz spectrum currently used by microwave cellular systems (concentrated in bands below 6 GHz)
- **Millimeter-wave communication: 30-300 GHz bands**
  1. Very high data rate and large number of antennas in a given device area (due to very small wavelength)
  2. Large path-loss especially with NLoS propagation, signal blocking/absorption
  3. Highly directional beams to improve link budget and enable dense spatial reuse (adaptive array processing algorithms, new MAC algorithms)
  4. Hardware constraints (power consumption of ADCs/DACs etc.)

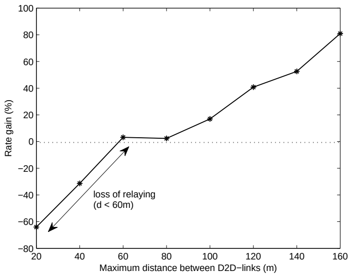
- D2D communication
  1. With overlay spectrum sharing, orthogonal spectrm bands are allocated to D2D and cellular links (also called *dedicated mode* of operation)
  2. With underlay spectrum sharing, the D2D links are allowed to reuse the spectrum occupied by cellular links in an opportunistic manner (also called *reuse mode* of operation).
  3. Potential D2D UEs can also relay their data through BS in the same way as cellular UEs (also called *cellular mode* of operation).
  4. With underlay spectrum access for D2D communication, cross-mode (cellular mode and reuse mode) interference degrades SINR for ongoing transmissions.
  5. Centralized (network controlled) vs. distributed (user-controlled) mode selection
  6. Protocol design for D2D communication

Enabling technologies for 5G

- Network-assisted D2D communication
  1. D2D UEs are supported by the relay nodes due to long distance and/or poor link condition between peers.
  2. LTE-A Layer-3 (L3) relays with self-backhauling configuration are capable of performing operations similar to those of a base station (i.e., Evolved Node B [eNB] in an LTE-A network).



- Gain in aggregated achievable data rate with varying distance. There is a critical distance d (i.e., $d \approx 60$m here), beyond which relaying provides significant performance gain.



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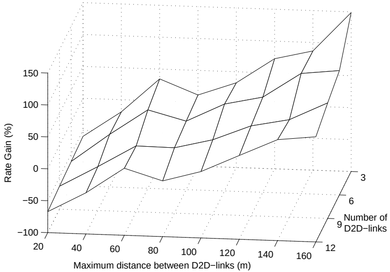

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M. Hasan and E. Hossain, "Resource allocation for nerwork-intrgrated device-to-device communications using smart relays," in International Workshop on Device-to-Device (D2D) Communication With and Without Infrastructure (GC13 WS - D2D) in conjunction with *IEEE Globecom'13*.

Enabling technologies for 5G

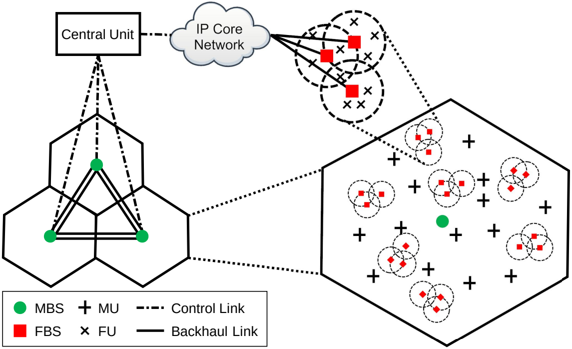
- Coordinated Multipoint (CoMP)/Network Multiple-Input Multiple-Output (N-MIMO)
  1. In downlink CoMP, BSs (or RRHs) cooperate in scheduling and transmission in order to strengthen the desired signal and mitigate inter-cell interference.
  2. Base stations exchange the users' data and their channel state information (CSI) and/or coordinate transmissions with each other where the signal processing is distributed among all the cooperating transmitters.
  3. Exploit high quality X2 connections between cooperating BSs or RRHs which are connected to the cooperating BSs through optical fiber links.
  4. Beamforming strategy, such as zero-forcing beam-forming (ZFBF), can be used to serve multiple users on the same subcarrier at the same time by choosing precoding coefficients to cancel out the co-tier interference.

- Downlink and uplink N-MIMO
  1. Joint Transmission (JT), Dynamic Point Selection (DPS), Dynamic Point Blanking (DPB), and Coordinated Scheduling/Beamforming (CS/CB).
  2. In JT, two or more BSs transmit a signal simultaneously on the same time/frequency resource to the UE. The UE, then, combines the received signals coherently or non coherently.
  3. In LTE, JT requires high capacity X2 interface between the cooperating BSs for sharing the transmit data.
  4. In DPS, the transmission points are varied according to the channel and interference conditions.
  5. DPS performance can be enhanced by using DPB which works by muting the dominant interfering BSs.

Enabling technologies for 5G

- Downlink and uplink N-MIMO
  1. In CS/CB, UE scheduling and beamforming takes place at multiple BSs to reduce interference. No data sharing between the cooperating BSs is required; however, channel state information and scheduling information are shared.
  2. Combination of the downlink CoMP schemes (i.e., hybrid modes) can be employed for transmission.
  3. Uplink CoMP is categorized into Joint Reception (JR) and Coordinated Scheduling (CS).
  4. In JR, the UE transmitted signal is received by multiple BSs, which is then transferred between the BSs and combined.

- CoMP/N-MIMO in multi-tier networks



Enabling technologies for 5G

- Multi-RAT virtual radio access networks
  1. Support multiple RATs (lincensed, unlicensed, higher frequency bands) with overlapping coverage into a single virtual RAN
  2. D2D communictaion based on WiFi Direct or LTE Direct
  3. WiGig (short-range mm-wave technology)
  4. Enable joint management and simultaneous use of radio resources across different radio technologies (improve capacity, coverage, and link reliability)
  5. Seamless application session
  6. Intelligent RRIM techniques across RATs will be required

Enabling technologies for 5G

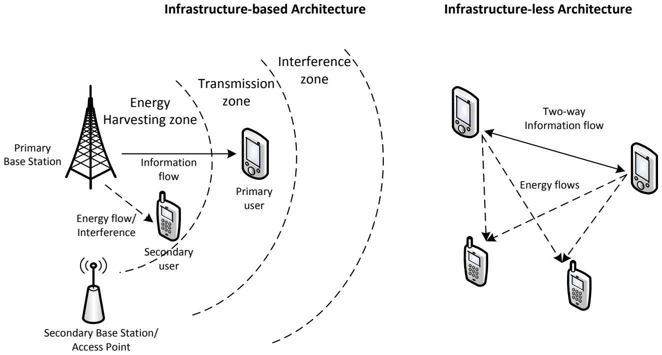
- Energy harvesting for energy efficient communication
  1. Harvest energy from environmental energy sources (e.g., solar and wind energy) and also from ambient radio signals (i.e., RF energy harvesting).
  2. Simultaneous wireless information and power transfer (SWIPT) is a promising technology 5G wireless networks.
  3. Practical circuits for harvesting energy are not yet available – conventional receiver architecture is designed for information transfer only and may not be optimal for SWIPT.
  4. Information and power transfer operate with different power sensitivities at the receiver (e.g., -10dBm and -60dBm for energy and information receivers, respectively).
  5. A combination of different energy harvesting technologies may be required for macrocell communication
  6. RF energy harvesting may be sufficient for short-range communication (e.g., for D2D communication or communication within a small cell).

Enabling technologies for 5G

- Experimental data on RF energy harvesting

Source	Source Power	Frequency	Distance	Amount of Energy Harvested
GSM900		935-960MHZ	25m-100m	$10^{-3} - 10^{-1}\mu$ W/cm^2
GSM1800		1805.2-1879.8MHZ	25m-100m	$10^{-3} - 10^{-1}\mu$ W/cm^2
AM Radio	50KW 50KW 5KW		5km 10km 2.5km	159μ W/m^2 40μ W/m^2 200μW
Mobile BS	100W 100W 100W		100m 500m 1000m	800μW/m^2 32μW/m^2 8μ W/m^2
Mobile Phone	0.5W 0.5W 0.5W	915 MHz 915MHz 915MHz	1m 5m 10m	40mW/m^2 1.6mW/m^2 0.4mW/m^2

- An energy harvesting cognitive radio network



- Part III: Interference management challenges in 5G multi-tier networks

Interference management challenges in 5G multi-tier networks

- Interference dynamics in the uplink and downlink is affected by
  1. Heterogeneity and dense deployment of radio devices
  2. Coverage and traffic load imbalance in the downlink
  3. Access restrictions (i.e., public or private) at the different network tiers
  4. Prioritized spectrum access: both traffic-based and tier-based priorities
  5. Carrier aggregation, BS cooperation, D2D communictaion further complicate the interference dynamics

Interference management challenges in 5G multi-tier networks

- Key challenges
  1. Efficient spectrum sharing among multiple network tiers
  2. Efficient techniques for carrier aggregation/carrier bonding
  3. Optimized cell association
  4. Simultaneous association to multiple BSs
  5. Distributed power control
  6. Efficient cooperation/coordination among BSs in multiple tiers
  7. Resource management in C-RAN
  8. Efficient resource allocation for energy harvesting communication

Interference management challenges in 5G multi-tier networks

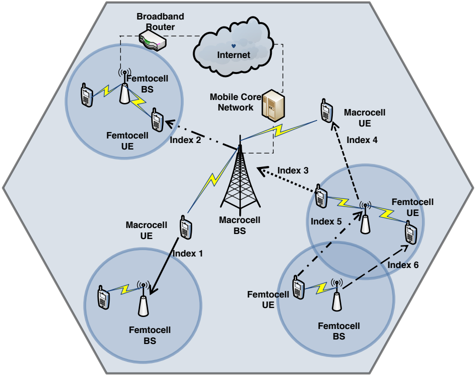
- Efficient spectrum sharing among multiple network tiers
  1. *Universal*, *orthogonal*, and *partially orthogonal* spectrum sharing
  2. Universal: adopted in LTE Rel-11, all added tiers will use the entire spectrum simultaneously. Although the spectrum efficiency is maximized, interference becomes a very critical issue.
  3. With orthogonal operation, each network tier will have its own dedicated spectrum. One of the suggestions for Rel-12 and beyond is to have the low frequency spectrum dedicated for the high power wide coverage tier, whereas high frequency spectrum to be allocated to the low power small coverage tier.
  4. Although the cross-tier interference is eliminated in orthogonal spectrum allocation, it results in reduced spectrum efficiency.

Interference management challenges in 5G multi-tier networks

- Efficient spectrum sharing among multiple network tiers
  1. With partially orthogonal spectrum sharing strategy, each tier can have its dedicated spectrum part and in the same time, some bands may be allowed to be used universally among different tiers.
  2. Specifying the optimal bandwidth to be allocated to each tier and the amount of spectrum to be shared is an optimization problem that needs careful investigation, taking into consideration the load in each tier, its priority and its intended coverage area.

Interference management challenges in 5G multi-tier networks

- Interference scenarios in a two-tier small cell network



Index	Aggressor	Victim	Interference Type	Transmission Mode	Symbol
1	Macrocell UE	Femtocell BS	Cross-tier	Uplink	——→
2	Macrocell BS	Femtocell UE	Cross-tier	Downlink	—··—··→
3	Femtocell UE	Macrocell BS	Cross-tier	Uplink	·········→
4	Femtocell BS	Macrocell UE	Cross-tier	Downlink	---------→
5	Femtocell UE	Femtocell BS	Co-tier	Uplink	-·-·-·-→
6	Femtocell BS	Femtocell UE	Co-tier	Downlink	— — —→

Interference management challenges in 5G multi-tier networks

- Interference between neighboring small cells, and between small cells and a macrocell.
- *Co-tier interference*: between same layer network elements, e.g., inter-femtocell interference or inter-macrocell interference.
- *Cross-tier interference*: between network elements that belong to the different tiers of the network, e.g., between femtocells and macrocell.
- Distributed interference management scheme is required which satisfies the QoS requirements of the users and at the same time enhances the capacity and coverage of the network.

Interference management challenges in 5G multi-tier networks

- Efficient techniques for CA/CB in OSA bands
  1. Ensure reliable availability of opportunistically aggregated spectrum
  2. Take into account the physical properties of channels
  3. Adaptively vary the number of aggegated channels
  4. Avoid aggegating channels in which independent PU incumbents can be active

Interference management challenges in 5G multi-tier networks

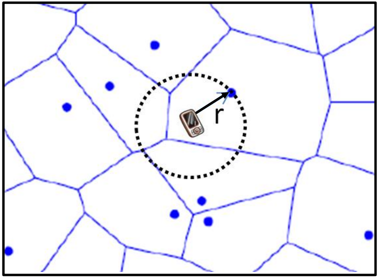
- Efficient techniques for carrier aggregation/carrier bonding in unlicensed bands
  1. Dynamic selection of channels in the 5 GHz band should avoid channels with radar (if present)
  2. Avoid channel leakage due to neighboring user transmissions with strong signal strengths
  3. Dynamic selection of modulation and coding scheme (MCS) to maximize the benefits of CB

Interference management challenges in 5G multi-tier networks

- Optimized cell association
  1. Cell association is needed to maximize spectral efficiency
  2. Cell association should consider the BS load as well as channel status of UEs
  3. Asymmetry in downlink and uplink association
  4. Optimal solutions for both uplink and downlink, or separate uplink and downlink optimal solutions

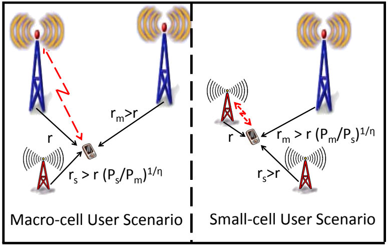
Interference management challenges in 5G multi-tier networks

- User association in single-tier networks
  1. User association, spectrum access methods, etc. affect network geometry (and hence SINR) and performance of resource allocation methods
  2. In a single-tier network with all BSs having the same transmit power, a user associates to the nearest BS (for which the average RSS is also the highest in the downlink).



Interference management challenges in 5G multi-tier networks

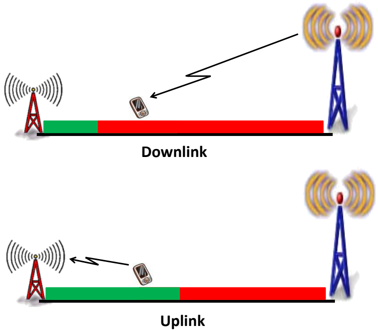
- User association in multi-tier networks
  1. Different BSs having different transmit powers.
  2. With the strongest RSS or SINR-based association, the BS may not necessarily be the closest one.
  3. Distance to the BS depends on relative transmit powers and propagation conditions.
  4. **Example**: In first fig., r is larger than r_s, but since $P_m r^{-\eta} > P_s r_s^{-\eta}$, $r \times (P_s/P_m)^{1/\eta} < r_s$.



Highest RSS Connectivity

Interference management challenges in 5G multi-tier networks

- User association in multi-tier networks
  1. Unbalanced uplink-downlink association
  2. In downlink, a user may associate with a macro BS, while in the uplink, it may associate with a small cell BS.



Interference management challenges in 5G multi-tier networks

- User association in multi-tier networks
  1. Traffic offloading and load balancing
  2. **Biasing** can be used in multi-tier cellular networks to offload users from one network tier to another tier.
  3. Biasing is known as **range extension** in the 3GPP standard.
  4. Instead of associating to the network entity offering the highest signal power, a user associates to a small cell if
  $$P_s T r_s^{-\eta} > P_m r_m^{-\eta}, \quad \text{where } T \geq 1.$$
  $$\text{i.e., if } r_m > \left(\frac{P_m}{P_s T}\right)^{\frac{1}{\eta}} r_s.$$
  5. Without biasing, $r_m > \left(\frac{P_m}{P_s}\right)^{\frac{1}{\eta}} r_s$, that is, biasing will **decrease** the minimum distance between a small cell user and interfering MBSs.

Interference management challenges in 5G multi-tier networks

- Efficient methods to support simultaneous association to multiple BSs
    1. Enhance system throughput and reduce outage ratio, paricularly for cell edge users
    2. Determine under which conditions a given UE is associated to which BSs in the uplink and/or downlink

Interference management challenges in 5G multi-tier networks

- Power control
  1. To control the intra-tier and inter-tier interferences in a distributed manner, power control allows the UEs to set their transmit power levels using the pertinent network information and minimal exchange of signaling information.
  2. Power control is required to minimize power (and hence minimize interference to other links) while keeping the desired link quality
  3. For power control, priorities of different users needs to be maintained.

Interference management challenges in 5G multi-tier networks

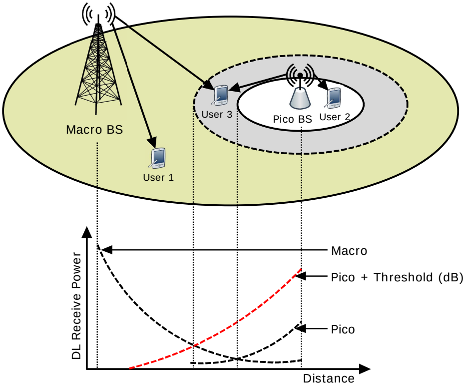
- Efficient design of N-MIMO techniques
  1. It is necessary to define a way in order to specify the coordinating set of BSs
  2. Tight synchronization is required between coordinating BSs in both frequency and time domain in order to avoid intercarrier interference as well as intersymbol interference.
  3. Exchange of UE data, channel state information and scheduling information among the coordinating BSs can be a huge burden on the backhaul.
  4. CoMP with channel uncertainties and background interference yields very low gains; therefore, should be designed carefully for 5G multi-tier networks.

Interference management challenges in 5G multi-tier networks

- Efficient methods for cooperation and coordination among multiple tiers
  1. Cooperation between macrocell and small cells proposed for LTE Rel-12 where UEs are allowed to have dual connectivity
  2. Will be a key method to mitigate interference in 5G networks
  3. CoMP schemes based on cooperation among BSs in different tiers can be developed to mitigate interference.
  4. Need to be adaptive and consider user locations as well as channel conditions to maximize spectral and/or energy efficiency

Interference management challenges in 5G multi-tier networks

- Cooperation and coordination among multiple tiers



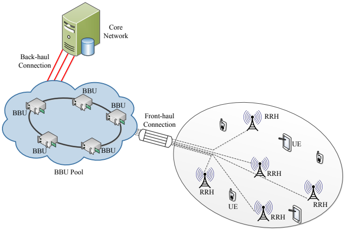
A. H. Sakr and E. Hossain, "Location-aware cross-tier coordinated multipoint transmission in two-tier cellular networks," *IEEE Transactions on Wireless Communications*. Available: [Online] http://home.cc.umanitoba.ca/∼sakra/publications.html

Interference management challenges in 5G multi-tier networks

- Each of User 1 and User 2 is served by only one BS that results in the maximum received power from any of the two tiers, User 3 is connected to more than one BS – one BS from each tier that results in the maximum received power from that tier.
- Although the power received at User 3 from the serving macro BS is higher than that of the interference resulting from the closest pico BS, the interference power from the closest pico BS can be comparable to the useful signal power which results in a low value of signal-to-interference-plus-noise ratio (SINR).
- Macro BS can cooperate with the interfering pico BS to serve User 3 jointly (eliminate strongest interference as well as increase useful signal power).

Interference management challenges in 5G multi-tier networks

- Resource management in C-RAN
  1. Each UE served by a specific group of RRHs, which receive corresponding baseband signals from cloud using fronthaul links
  2. In **downlink**, RRHs transmit RF signals formed by using baseband signals received from BBUs; in **uplink**, RRHs forward the baseband signals from UEs to the BBU pool



Vu N. Ha, Long B. Le, and Ngoc-Dung Dao, "Cooperative transmission in Cloud RAN considering fronthaul capacity and cloud processing constraints, in Proc. *IEEE WCNC'14*.

Interference management challenges in 5G multi-tier networks

- Resource management in C-RAN
  1. Radio over low-cost optical network (10 Gbps, strict delay and jitter requirements)
  2. Both end-user data and UL/DL channel information need to be shared among virtual BSs
  3. Optimal utilization of the processing resources and efficient usage of the fronthaul links connecting BBUs with RRHs
  4. Efficient allocation of the BBUs and RRHs to UEs
  5. Advanced cooperative transmission/reception (joint scheduling of radio resources to reduce interference) considering fronthaul constraints

Interference management challenges in 5G multi-tier networks

- Resource management in C-RAN
  1. Virtualization technologies for the BS proessing pool (real-time processing algorithms, dynamic allocation of processing capacity)
  2. Virtualization refers to the abstraction of computer resources.
  3. Efficient and flexible real-time virtualized operating system to achieve virtualization of hardware resources and dynamic allocation of physical resources to each virtual base station
  4. General purpose processor and advancecd processing algorithm for real-time signal processing
  5. Software-defined radio (SDR)-based baseband processing to support multiple standards
  6. Real-time cloud infrastucture for virtual BSs

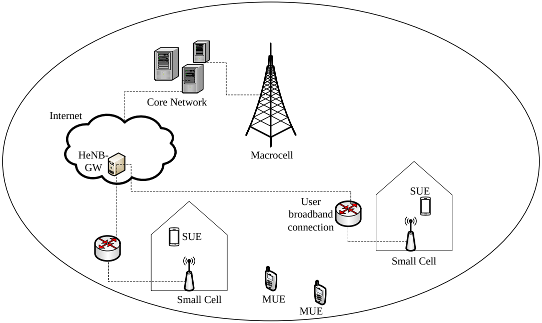
Interference management challenges in 5G multi-tier networks

- Efficient resource allocation for energy harvesting communication
  1. Data packet arrival as well as energy arrival (which are random processes) need to be considered for designing packet scheduling and transmission policies (to adjust transmission power, rate, and sequence of packets transmitted).
  2. Unavailability of non-causal (future) information of time and amount of energy harvested
  3. Complexity of online agorithms is very high compared to offline algorithms
  4. Typical objectives for power allocation: Maximize throughput, minimize outage probability, minimize power consumption from fixed power source (e.g., power grid)
  5. Typical objectives for packet scheduling: minimize transmission time/maximize throughput

- Part IV: Tier-aware downlink resource allocation in multi-tier OFDMA networks

Tier-aware downlink resource allocation in multi-tier OFDMA networks

- OFDMA-based two-tier macrocell-small cell network



A. Abdelnasser, E. Hossain, and D. I. Kim, "Tier-aware resource allocation in OFDMA macrocell-small cell networks," submitted to the *IEEE Transactions on Wireless Communications*. Available [Online]: http://arxiv.org/abs/1405.2000

Tier-aware downlink resource allocation in multi-tier OFDMA networks

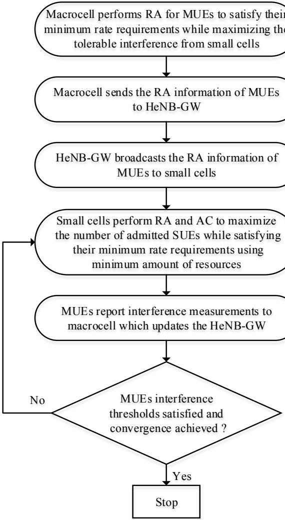
- Traditional methods of resource allocation (RA)
  1. Maximize sum-rate for the two tiers with/without QoS constraints for MUEs, with/without admission control (AC)
  2. Maximize sum rate for small cells with QoS constraints for MUEs and/or SUEs
  3. Minimize sum-power with maximum number of SUEs
  4. Maximize the product of the minimum of (2$\times$target rate - achieved rate, achieved rate)

Tier-aware downlink resource allocation in multi-tier OFDMA networks

- RA in one tier cannot be done in isolation with the RA in other tiers.
- Considering the existence of small cells, the macrocell allocates the resources to its MUEs in a way that can sustain the highest interference level from the small cells while satisfying the minimum data rate requirements of MUEs.
- Knowing about the maximum allowable interference levels for MUEs, the small cells perform RA with an objective to admitting as many small cell UEs (SUEs) as possible at their target data rates and consume the minimum amount of bandwidth.
- Leave as much bandwidth as possible for other possible network tiers (e.g., for D2D communication)

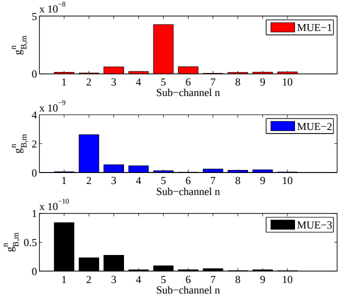
Tier-aware downlink resource allocation in multi-tier OFDMA networks

- RA framework



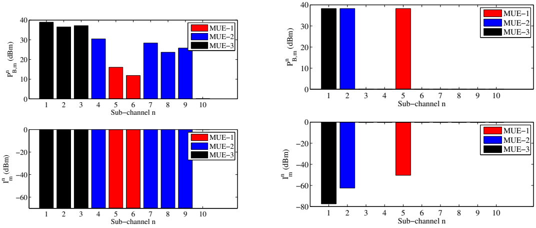
Tier-aware downlink resource allocation in multi-tier OFDMA networks

- Channel gains $g_{B,m}^{n}$ for MUEs $\{1, 2, 3\}$



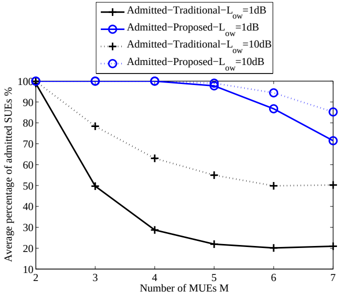
Tier-aware downlink resource allocation in multi-tier OFDMA networks

- Allocated power $P^n_{B,m}$ and maximum tolerable interference level I^n_m for MUEs $\{1, 2, 3\}$: traditional method vs. "tier-aware" method



Tier-aware downlink resource allocation in multi-tier OFDMA networks

- Average percentage of admitted SUEs vs. number of MUEs *M* under different wall loss scenarios



- Part V: Distributed cell association and power control schemes

- Distributed cell association schemes
- Distributed power control schemes
- Joint cell association and power control (CAPC) schemes
- Design guidelines for distributed CAPC schemes for 5G multi-tier networks

Distributed cell association schemes

- Reference signal received power (RSRP)-based scheme
- Biasing-based cell range expansion (CRE) scheme
- Association based on Almost Blank Subframe (ABS) ratio

Distributed cell association schemes

- RSRP scheme
    1. A user associates with the BS whose signal is received with the largest average strength
    2. A variant – Reference Received Signal Quality (RSRQ) scheme, which is similar to SIR-based cell selection
    3. RSRQ may maximize throughput in single-tier networks.
    4. In multi-tier networks, it can create huge traffic load imbalance by overloading the high power tiers.

- CRE scheme
  1. Remedy to the problem of load imbalance in the downlink
  2. Increases the downlonk coverage footprint of low-power BSs (*biased BSs*) by adding a positive bias to their signal strengths
  3. Off-loaded users may experience unfavorable channel from biased BSs and strong interference from unbiased high-power BSs.
  4. Trade-off between cell load balancing and system throughput depends on the bias values, which need to be optimized to maximize system utility.
  5. Orthogonalize transmissions of biased and unbiased BSs in time/frequency domain (create interference-free zone)

Distributed cell association schemes

- ABS technique
  1. Uses time-domain orthogonalization – specific subframes are left blank by the unbiased BS and off-loaded users are scheduled within these subframes to avoid cross-tier interference
  2. Improves overall throughput of the off-loaded users by sacrificing throughput of unbiased BS
  3. Larger bias values require more blank subframes to protect the offloaded users
  4. Given an ABS ratio (i.e., ratio of blank over total number of subframes), a user may select a cell with maximum ABS ratio
  5. A user may associate with the unbiased BS if ABS ratio decreases significantly.

Distributed cell association schemes

	RSRP	RSRQ	CRE	ABS
Objective	Max. received signal power	Max. SIR	Balance traffic load	Max. rate, balance load
Applicability	Uplink and downlink	Uplink and downlink	Downlink	Downlink
Channel-aware	✓	✓	✓	✓
Interference-aware	X	✓	✓	✓
Traffic load-aware	X	X	✓	✓
Resource-aware	X	X	X	✓
Priority-aware	X	X	X	✓

Distributed power control schemes

- Support a user with minimum acceptable throughput (from a user's perspective)
  1. Allocate higher power levels to users with poor channels
- Maximize aggregate throughput (from system's perspective)
  1. High power levels allocated to users with best channels
- Performance measures: aggregate transmit power, outage ratio, aggregate throughput of UEs
- Numerous power control schemes for single-tier cellular networks
  1. Target SIR-tracking power control (TPC)
  2. TPC with gradual removal (TPC-GR)
  3. Opportunistic power control (OPC)
  4. Dynamic SIR tracking power control (DTPC)

Distributed power control schemes

- TPC
  1. Each UE tracks its own predefined target-SIR
  2. UEs achieve their target-SIRs at minimal aggregate transmit power, assuming that the target-SIRs are feasible
  3. When the system is infeasible, all non-supported UEs (who do not obtain their target-SIRs) transmit at their maximum power (hence unnecessary power consumption and interference to other UEs and increased outage ratio)
- TPC-GR: Non-supported UEs reduce transmit power or gradually removed

G. Foschini and Z. Miljanic, "A simple distributed autonomous power control algorithm and its convergence," *IEEE Trans. Veh. Technol.*, vol. 42, no. 4, pp. 641-646, 1993.

M. Rasti and A.-R. Sharafat, "Distributed uplink power control with soft removal for wireless networks," *IEEE Trans. Comm.*, vol. 59, no. 3, pp. 833-843, 2011.

Distributed power control schemes

- OPC
  1. Allocates high power levels to users with good channels (i.e., high path-gains and low interference levels) and low power to users with poor channels
  2. A small difference in path-gains between two users may lead to a large difference in their actual throughputs
  3. Improves system performance at the cost of reduced fairness

K.-K. Leung and C.-W. Sung, "An opportunistic power control algorithm for cellular network," *IEEE/ACM Trans. Networking*, vol. 14, no. 3, pp. 470-478, 2006.

Distributed power control schemes

- DTPC

  1. TPC causes UEs to exactly hit their fixed target-SIRs even if additional resources are still available (i.e., higher SIR and thus better throughput could be achieved).
  2. Fixed target-SIR may be only suitable for voice service, not for data service
  3. DTPC addresses the problem of system throughput maximization subject to a given lower bound for the acheived SIRs for all users.
  4. When the minimum acceptable target-SIRs are feasible, actual SIRs received by some users can be increased in a distriubuted manner (so far as the system remains feasible).
  5. Enhances system throughput at the cost of higher power consumption, when compared to TPC

M. Rasti, A.-R. Sharafat, and J. Zander, "A distributed dynamic target SIR-tracking power control algorithm for wireless cellular networks," *IEEE Trans. Vehicular Technol.*, vol. 59, no. 2, pp. 906-916, 2010.

Distributed power control schemes

- Distributed power control schemes for single-tier networks are unable to address the interference management problem in 5G multi-tier networks
- Do not guarantee that the total interference caused by the low-priority UEs (LPUEs) to the high-priority UEs (HPUEs) remains within the tolerable limit
- Modify the exisiting schemes such that low-priority UEs track their objectives while limiting their transmit power to maintain a given interference threshold at high-priority UEs

Joint cell association and power control (CAPC) schemes

- Distributed and optimal/sub-optimal with guaranteed convergence

Yates95 : Uplink cell selection based on effective interference (ratio of instantaneous interference and channel gain) at the BSs

- Minimizes aggregate uplink transmit power while attaining users' taget-SIRs

Vu'14 : A unified distributed algorithm for two-tier networks

- Cell association is based on effective interference and integrated with a hybrid power control (HPC) scheme, which is a combination of TPC and OPC algorithms.

R. D. Yates and C.-Y. Huang, "Integrated power control and base station assignment," *IEEE Trans. Vehi. Technol*, vol. 44, no. 3, pp. 638-644, 1995.

H. N. Vu and L. B. Le, "Distributed base station association and power control for heterogeneous cellular networks," *IEEE Trans. Vehi. Technol.*, vol. 63, no. 1, pp. 282-296, 2014.

Joint cell association and power control (CAPC) schemes

- Interference dynamics in multi-tier networks depends on priority of different tiers, UEs' QoS requirements, channel scheduling at different tiers
- For 5G networks, existing CAPC should be modified to include various types of cell selection methods and power control methods with different objectives and interference constraints (i.e., interference constraints for macrocell UEs, picocell UEs, D2D receiver UEs)
- Each user can possibly simultaneously connect to multiple BSs (can be different for uplink and downlink) while achieving load balancing in different cells and guaranteeing interference protection for high-priority UEs.

Design guidelines for distributed CAPC schemes for 5G multi-tier networks

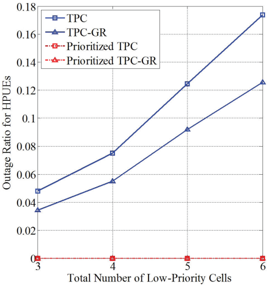
- Prioritized power control
- Resource-aware cell association
- Resource-aware cell association and prioritized power control

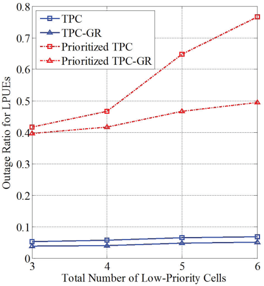
Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Prioritized power control
  1. LPUEs limit their transmit power to keep interference caused to HPUEs below a predefined threshold, while tracking their own objectives.
  2. As long as HPUEs are protected, LPUEs can use exisiting distributed power control algorithms.
- Different objectives
  1. With fixed BS assignment, minimize aggregate power subject to minimum (different) target-SIRs for users in different tiers.
  2. Minimize outage ratio of LPUEs subject to zero-outage for HPUEs.
  3. Maximize aggregate throughput of all users subject to zero-outage for HPUEs.
  4. Maximize aggregate throughput of LPUEs subject to minimum target-SIR of all users.

Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Prioritized power control
  1. In addition to setting their transmit power for tracking their objectives, the LPUEs limit their transmit power to keep interference caused to HPUEs below a given threshold.
  2. HPUEs can notify the nearby LPUEs when the interference exceeds the given threshold.





Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Prioritized power control
  1. A two-tier system (high-priority cell tier and low-priority cell tier) with same target SIR for all users
  2. 5 HPUEs per high-priority cell and 4 LPUEs per low-priority cell, each user is associated with only one BS of its corresponding tier.
  3. LPUEs employ either TPC, TPC-GR, prioritized TPC, or prioritized TPC-GR, and HPUEs use TPC (i.e., rigidly track their target-SIRs).
  4. Although outage ratio for HPUEs are improved by TPC-GR, as compared to TPC, protection of HPUEs is not guaranteed. Prioritized TPC and TPC-GR guarantee protection of HPUEs at the cost of increased outage ratio for LPUEs.
  5. Also, with prioritized OPC for LPUEs and TPC for HPUEs, protection of HPUEs is guaranteed at the cost of decreased throughput for LPUEs (compared to non-prioritized OPC).

Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Resource-aware cell association schemes
  1. Balance the traffic load as well as minimize interference or maximize SIR levels
  2. For load balancing, CRE technique forces the users to select low power nodes by adding fixed bias. But it does not consider the resource allocation criterion in the corresponding cell.
  3. Bias selection should be adaptive to the resource allocation criterion, traffic load, and distance/channel corresponding to the different BSs.
  4. New resource-aware cell association criterion: each user selects a BS with *maximum channel access probability* (i.e., $max\{p_i\}$).

Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Resource-aware cell association schemes
  1. p_i varies for different resource allocation criteria, e.g., with round-robin scheduling, p_i is reciprocal of the number of users.
  2. For greedy scheduling, p_i is the probability that the channel gain of the newly associated user is higher than the channel gain of all exisiting users in cell i. Hence it depends on both the channel condition and the number of users in cell i.
  3. Proposed criterion p_i provides an adaptive biasing to different BSs.
  4. With *distance-aware cell association*, each user selects a cell with minimum distance which tends to maximize the sum-rate performance. However, this criterion does not consider traffic load conditions.

Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Hybrid cell association scheme
  1. Combine resource-aware and distance-aware criteria
  2. A user selects a cell with the maximum of product of distance-based channel gain and p_i.
  3. If $p_i = 0$ (i.e., high or infinite traffic load), a user will not select cell i even if it is the closest cell and vice versa.
  4. Hybrid scheme achieves a balance between traffic load balancing and throughput maximization.
  5. Quantitative comparison among resource-aware, distance-aware, and hybrid cell association schemes: two-tier macrocell-small cell network, downlink transmission, round-robin scheduling

Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Hybrid cell association scheme

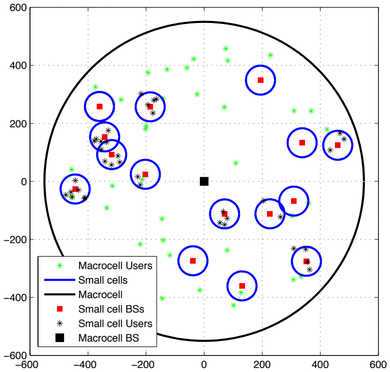
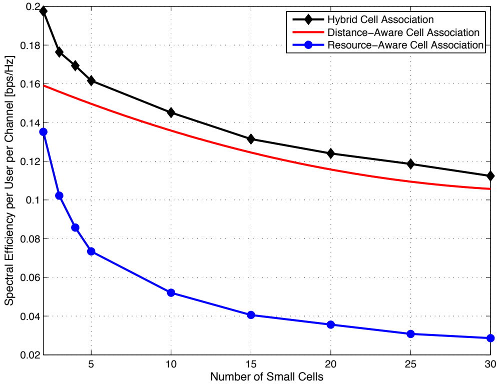


Figure: A circular macrocell with several small cells. Each small cell has varying user traffic load.

Design guidelines for distributed CAPC schemes for 5G multi-tier networks

Comparison among distance-aware, resource-aware, and hybrid cell-association schemes (for path-loss exponent = 4, macrocell transmit power = 10 W and small cell transmit power = 1 W):



Design guidelines for distributed CAPC schemes for 5G multi-tier networks

- Resource-aware cell association and prioritized power control
  1. Cell association methods can be combined with prioritized power control schemes depending on the desired objectives.
  2. Select a correct combination of cell-association and power control methods.
  3. Joint minimum effective-interference-based cell association and OPC is not capable of maximizing throughput in the uplink.
  4. In conjunction with OPC, it may be useful to consider RSRP or RSRQ-based cell association.

- Part VI: Cognitive spectrum access by small cells

Cognitive spectrum access by small cells

- Spectrum sensing range and spectrum reuse efficiency
- Spectrum access schemes by cognitive small cells
  1. Performance gain due to opportunistic spectrum access
  2. Effect of channel allocation at the macro tier
- Clustering-based spectrum access by cognitive small cells

Spectrum sensing range and spectrum reuse efficiency

- **Interference** is the most performance limiting parameter in multi-tier small cell networks
- Infeasible to use traditional centralized techniques to coordinate spectrum access by a large number of small cells
- A cognitive small cell will not access a channel unless the power received on that channel from any other network entity is less than the spectrum sensing threshold.
- Due to the distance-dependent signal power decay, the spectrum sensing threshold defines an area where no interference source exists.

Spectrum sensing range and spectrum reuse efficiency

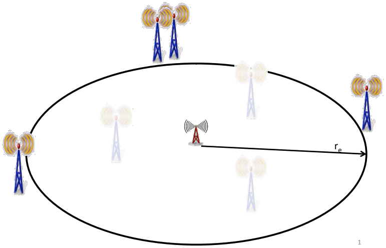
- A channel used by a network entity (i.e., an MBS or an SBS) located at $x \in \mathbb{R}^2$ can be reused by a cognitive SBS located at $y \in \mathbb{R}^2$ if and only if

$$\|x - y\| \geq \left(\frac{P_{tx} h(x, y)}{\gamma} \right)^{\frac{1}{\eta}} \qquad (1)$$

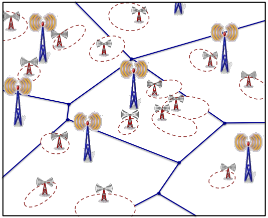
  where $h(x, y)$ = random channel gain between the two locations x and y, P_{tx} = transmit power of the network entity located at x, γ = **spectrum sensing threshold**, $\|.\|$ = Euclidean norm, and η = path-loss exponent.
- γ is the design parameter that controls the minimum frequency reuse distance $r_e = \left(\frac{P_{tx} h(x,y)}{\gamma} \right)^{\frac{1}{\eta}}$ and hence the spatial reuse efficiency.

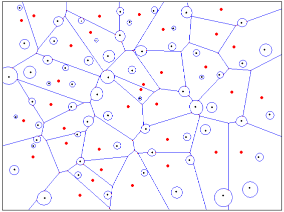
Spectrum sensing range and spectrum reuse efficiency

- Higher the value of γ, lower is the frequency reuse distance and more aggressive will be the cognitive SBSs in spectrum access (hence increased mutual interference leading to a higher outage probability, and vice versa).
- Tradeoff between spatial frequency reuse efficiency and outage probability that can be optimized by carefully tuning the spectrum sensing threshold



- Network modeling
  1. With multiple network tiers, more randomness is introduced to the network topology.
  2. Due to the transmit power variation, the coverage follows the weighted Voronoi tessellation.





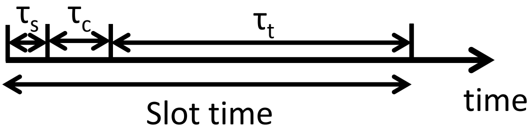
Spectrum access schemes by cognitive small cells

- Network modeling
  1. Network topology is abstracted by a point process (e.g., Poisson point process [PPP]) and interference is treated as a function of that point process.
  2. $\mathcal{I}(y) = \sum_{x_i \in \mathbf{\Psi}} g(x_i, y)$, where $g(x_i, y) = P h_i \left\| x_i - y \right\|^{-\eta}$.
- Using results from stochastic geometry, we can evaluate
  1. $\mathbb{E}\left[\sum_{x_i \in \mathbf{\Psi}_{\mathcal{I}}} g(x_i)\right]$ by using Campbell's theorem
  2. $\mathbb{E}\left[\prod_{x_i \in \mathbf{\Psi}_{\mathcal{I}}} g(x_i)\right]$ by using the probability generating functional (PGFL)
- Generally, we cannot find the *pdf* or *cdf* of aggregate interference. However, the LT (or CF, or MGF) of the *pdf* of interference can be obtained for any fading scenarios.
- The *cdf* of SIR or the lower/upper bounds on the *cdf* of SIR can be obtained for any fading distribution (in both useful and interference links).

- Network modeling
  1. Macro BSs are spatially distributed according to the homogeneous PPP $\mathbf{\Psi}_b = \{b_i; i = 1, 2, 3, ...\}$ with intensity $\mathcal{B}$
  2. SBSs are spatially distributed according to an independent homogeneous PPP $\mathbf{\Psi}_a = \{a_i; i = 1, 2, 3, ...\}$ with intensity $\mathcal{A}$
  3. User equipments (UEs) are spatially distributed according to an independent homogeneous PPP $\mathbf{\Psi}_u = \{u_i; i = 1, 2, 3, ...\}$ with intensity $\mathcal{U}$
  4. Both the network tiers share the same set of channels **S**.
  5. Channels have a specific order known to all macro BSs.
  6. All macro BSs transmit with the same power P_b.
  7. All SBSs (e.g., FAPs) transmit with the same power P_a.
  8. Macro BSs and SBSs always have packets to transmit in the downlink.

Spectrum access schemes by cognitive small cells

- Spectrum access by cognitive small cells

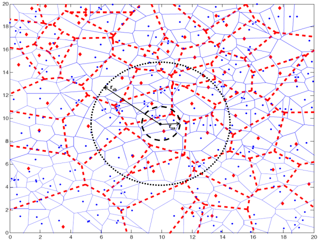


H. ElSawy and E. Hossain, "Two-tier HetNets with cognitive femtocells: Downlink performance modeling and analysis in a multi-channel environment," *IEEE Transactions on Mobile Computing*, to appear

Spectrum access schemes by cognitive small cells

- A cognitive small cell will not access a channel which is being used by nearby macocell and small cells.
- Unavailability of radio channels may lead to outage.
- Each time slot is divided into three main parts (**scheme-1**).
  1. *First part*: each cognitive small cell senses the available spectrum to detect the channels which are not used by the MBS.
  2. *Second part*: each cognitive small cell contends to access one of the available channels (e.g., using a random backoff process while persistently sensing the channel).
  3. *Third part*: if the sensed channel was available during the entire backoff duration (i.e., not used by any BS), the cognitive small cell transmits on that channel for the rest of the time slot. Otherwise, the small cell is considered to be in outage due to channel unavailability.

- Due to the unified sensing threshold γ each cognitive SBS (e.g., FAP) will have two spectrum sensing regions (SSR).
  1. *macro SSR*
  2. *small cell SSR*
- A cognitive SBS (e.g., FAP) should avoid using any channel used by a macro BS in the *macro SSR* and any channel used by any SBS in the *small cell SSR*.



Spectrum access schemes by cognitive small cells

- For downlink transmission, total outage probability for a small cell user can be expressed as

$$P_{out} = (1 - \mathbb{P}\{\text{opportunistic access}\}) + \mathbb{P}\{\text{SINR} \leq \beta\}\, \mathbb{P}\{\text{opportunistic access}\}$$

  where SINR is the signal-to-interference-plus-noise ratio and β is the threshold defined for correct signal reception.
- Both the opportunistic spectrum access probability and the SINR outage probability depend on the network geometry.
- Stochastic geometry tools can be used to evaluate performance metrics such as the outage probability (i.e., the probability that the SINR at a receiver falls below a target threshold) and network capacity (i.e., the total number of active users per unit area that can be accommodated by the network) in simple closed-form equations.

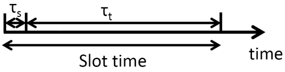
- Outage could be due to channel unavailability for opportunistic access and/or due to SINR violation (i.e., resulting from aggregate interference).
- Spectrum sensing threshold controls the tradeoff between the two outages.
- Increasing the spectrum sensing threshold decreases the frequency reuse distance and increases the opportunistic channel access, however, it increases the aggregate interference and hence the SINR outage.
- Decreasing the sensing threshold will increase the frequency reuse distance and hence decrease the aggregate interference, and therefore, decrease the SINR outage. However, the outage due to opportunistic channel access may increase due to increased contention resulting from higher number of SBSs and MBSs within the frequency reuse distance.

Spectrum access schemes by cognitive small cells

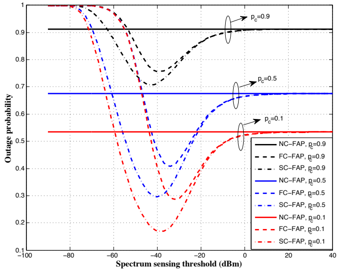
- For a given spectrum sensing threshold, since the opportunistic spectrum access performance of the small cells will deteriorate when the intensity of the deployed small cells is high, introducing spectrum awareness at a small cell with respect to the spectrum usage at the other small cells may not be the best solution.
- Instead, cognition can be introduced only with respect to the macro-tier. That is, each SBS senses the spectrum to locate the channels which are not used by the MBS and uses any of them without considering the other SBSs (**scheme-2**).

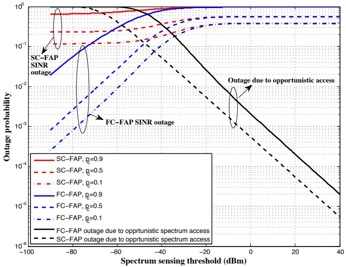
Spectrum access schemes by cognitive small cells

- Each time slot is divided into two main parts (**scheme-2**).
  1. *First part*: each cognitive small cell senses the available spectrum to detect the channels which are not used by the macrocell.
  2. *Second part*: each cognitive small cell selects one of the available channels and transmits in that channel.
- Channels will be aggressively used in the small cell tier to increase their opportunistic spectrum access performance at the expense of higher mutual interference in the small cell tier.



- Performance gain due to cognitive spectrum access
  1. Outage probability (of small cell users) vs. spectrum sensing threshold for cognitive techniques and different values p_c ($=$ percentage of SBSs operating in the closed access mode)
  2. Outage due to SINR violation and outage due to unavailability of channel for opportunistic spectrum access for small cell users vs. spectrum sensing threshold for different cognitive techniques and different values p_c





Spectrum access schemes by cognitive small cells

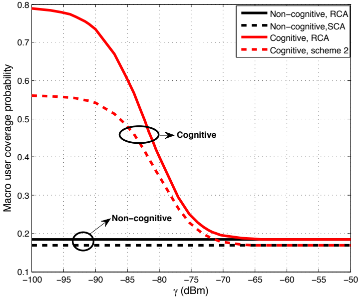
- There exists an optimal spectrum sensing threshold that depends on the network parameters and the cognition technique.
- A higher value of spectrum sensing threshold results in shorter frequency reuse distances and more spectrum opportunities, however, the aggregate interference increases and dominates the outage probability. This results in a degraded outage performance.
- For very high values of spectrum sensing threshold, the cognitive small cells become very aggressive and their performance matches with that of the non-cognitive small cells.
- Lower values of spectrum sensing threshold result in higher frequency reuse distance and lower aggregate interference; however, the opportunistic spectrum access probability decreases and dominates the outage probability.

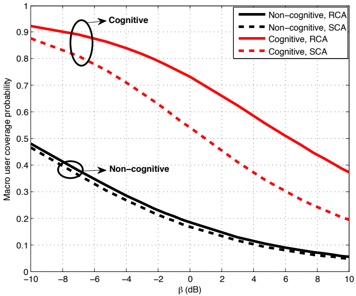
- Summary of observations
  1. For **scheme-1**, the decreased SINR outage probability is wasted by the outage probability due to the channel unavailability.
  2. The degraded SINR outage probability of **scheme-2** is balanced by the improved spectrum access probability.
  3. Cognition is an important feature that can significantly enhance the performance of small cell networks.
  4. Introducing cognition w.r.t. the macro-tier only is more beneficial than introducing cognition w.r.t. the two network tiers (due to uncoordinated access among densely deployed coexisting small cells).

- Effect of channel allocation at the macro tier

    1. Two channel assignment techniques for the MBSs in in a two-tier network with cognitive SBSs: random channel assignment (RCA) and sequential channel assignment (SCA)
    2. RCA: each MBS randomly and uniformly chooses one channel for each of its associated users
    3. SCA: the available channels have a specific order and each MBS assigns the channels to its associated users in a sequential manner.
    4. RCA deteriorates the opportunistic spectrum access performance for cognitive SBSs.
    5. SCA minimizes the number of unique channels used by the coexisting MBSs (hence maximizes the opportunistic spectrum access performance for cognitive SBSs)

- Effect of channel allocation at the macro tier
  1. SINR performance for macro users with varying spectrum sensing threshold (γ) and SINR threshold (β)

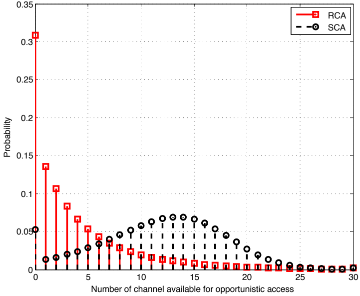


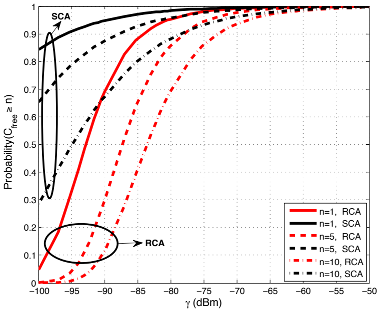


H. Elsawy and E. Hossain, "Channel assignment and opportunistic spectrum access in two-tier cellular networks with cognitive small cells," in Proc. of *IEEE Globecom 2013*.

Spectrum access schemes by cognitive small cells

- Independent random channel assignment highly degrades the opportunistic spectrum access probability for the SBSs.
- Probability that a generic SBS accesses a higher number of channels under the SCA scheme is quite larger than that under the RCA shceme.





Clustering-based spectrum access by cognitive small cells

- The concept of clustering may be used to optimize the tradeoff between the outage due to opportunistic spectrum access and outage due to the aggregate interference.
- In clustering, adjacent small cells group together and elect a cluster head to coordinate the spectrum access within the cluster.
- Many challenges need to be addressed to implement clustering.
  1. What is the optimal cluster size
  2. What information is to be exchanged among the cluster members
  3. How to elect the cluster head
  4. What is the allocation strategy that maximizes the throughput in the small cells while maintaining fairness among the cluster members.

- Part VII: Mode selection and power control for underlay D2D communication

Mode selection and power control for underlay D2D communication

- Biasing-based mode selection and channel inversion power control
- Cognitive and energy harvesting-based D2D communictaion

H. ElSawy and E. Hossain, "Analytical modeling of mode selection and power control for underlay D2D communication in cellular networks," submitted to the *IEEE Transactions on Communications*. Available: [Online] http://arxiv.org/abs/1405.2017

A. Sakr and E. Hossain, "Cognitive and energy harvesting-based D2D communication in cellular networks: Stochastic geometry modeling and analysis," submitted to the *IEEE Journal on Selected Areas in Communications*. Available: [Online] http://arxiv.org/abs/1405.2013

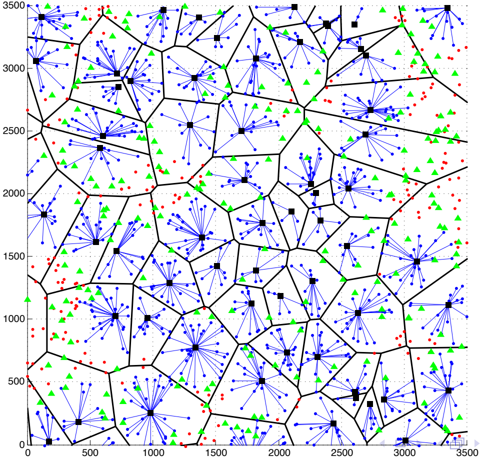
Biasing-based mode selection and power control

- Mode selection accounts for both D2D link quality and cellular link quality
- Biasing-based mode selection scheme with parameter T_d (bias factor)
- A potential D2D transmitter chooses the D2D mode if $T_d r_d^{-\eta_d} > r_c^{-\eta_c}$, where r_d is the D2D link distance, r_c is the distance between the UE and its closest BS (i.e., cellular uplink distance)
- Captures the disabled D2D mode of communication (i.e., when $T_d = 0$), the enforced D2D communication (i.e., when $T_d = \infty$), and the distance-based mode selection as special cases
- In D2D mode, UEs use a truncated channel inversion power control.
- Performance metrics: SINR outage probability, average transmit power, link capacity, and total network capacity

Biasing-based mode selection and power control

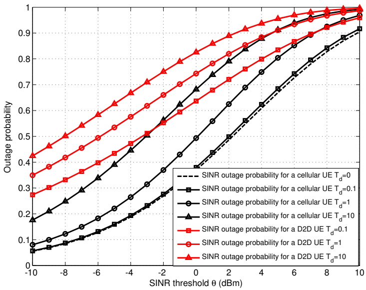
- UEs (i.e., potential transmitters) associate with their nearest BSs.
- In the D2D mode, for a transmitter UE, the receiver UE does not need to be in the same cell.
- A connection (i.e., cellular uplink or D2D link) is established if and only if the transmit power required for the path-loss inversion (to keep the average signal power received at the intended receiver equal to certain threshold ρ_o) is less than or equal to P_u, the maximum transmit power constraint
- Interference from a generic D2D transmitter received at a generic BS is strictly less than $T_d \rho_o$ (since transmitted power $= \rho_0 r_d^{\eta}$ and hence interference $= \rho_0 r_d^{\eta} r_c^{-\eta}$), where the bias factor T_d can be used to control the interference temperature at the BSs.
- SINR capture model: if the SINR at the receiver does not exceed the threshold θ, the link experiences an outage (SINR *outage*).

- Black squares represent the BSs, the blue dots represent the cellular UEs, blue lines indicate the uplink connections, red dots represent users in truncation outage, and the green triangles represent the D2D transmitters.

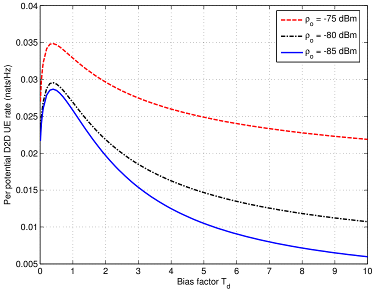


Biasing-based mode selection and power control

- Effect of T_d on SINR outage
  1. Increasing T_d increases the intensity of UEs selecting the D2D mode, decreases the interference protection around the cellular BSs.
  2. Hence, increasing T_d increases the SINR outage probability.
  3. Increasing ρ_o improves SINR outage.

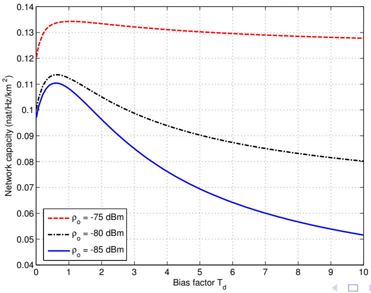


- Effect of T_d on average rate for a D2D link
  1. At low T_d, most of the D2D UEs operate in the cellular mode.
  2. For $T_d > 1$, UEs need more power to invert the channel towards the D2D receiver when compared to the power required to invert the channel towards the nearest BS in cellular mode (hence higher interference).



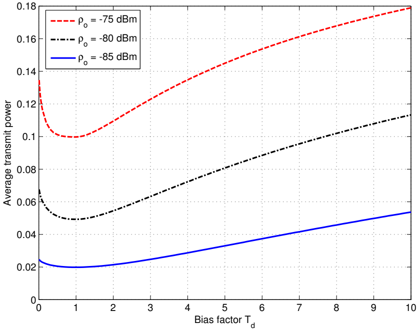
Biasing-based mode selection and power control

- Effect of T_d on total network capacity
  1. With proper adjustment of biasing threshold T_d, total network capacity can be maximized.
  2. D2D communication improves spatial frequency reuse efficiency, and hence, increases total network capacity.
  3. For high values of T_d, total network capacity deteriorates as a result of the poor SINR performance due to the increased intensity if interfering D2D UEs and the decreased interference protection region around cellular BSs.



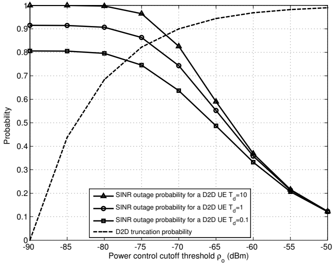
Biasing-based mode selection and power control

- Effect of T_d on expected transmit power of a potential D2D UE
  1. D2D communication can also be exploited to decrease the transmit powers of the potential D2D UEs.
  2. $T_d = 1$ is the optimal biasing factor that minimizes the transmit powers of the UEs.
  3. Increasing ρ_o increases the average transmit power of UEs.



Biasing-based mode selection and power control

- Effect of power control cutoff threshold ρ_0
  1. At low values of ρ_o, SINR dominates the outage probability due to the low power of the useful signal.
  2. Increasing ρ_o increases the power of the useful signal and decreases the SINR outage probability at the expense of increased truncation outage probability.



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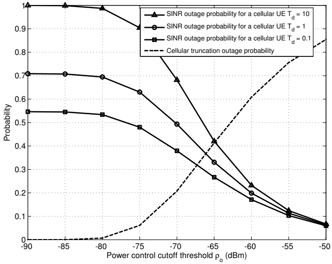

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Biasing-based mode selection and power control

- By setting $T_d = \infty$ and manipulating the D2D link distance via the truncation outage (i.e., by varying ρ_o), the model reduces to the distance-based mode selection scheme.
- Note that for D2D UEs, the truncated channel inversion power control results in the D2D proximity to $R = \left(\frac{P_u}{\rho_o}\right)^{\frac{1}{\eta_d}}$
- For any value ρ_o, setting a high value of T_d results in a high SINR performance degradation (i.e., outage and rate) $\Longrightarrow$ considering the D2D link distance only as the mode selection criterion will not provide an efficient solution to the mode selection (hence interference management) problem.
- Biasing introduces a fine-tuned control for mode selection.
- Enforcing all potential D2D UEs to communicate in the D2D mode results in a significant degradation in network performance.

Cognitive and energy harvesting-based D2D communictaion

- Consider cognitive D2D communication underlaying a multi-channel cellular network where the D2D transmitters are able to use only the harvested RF energy from the ambient interference that results from the concurrent downlink transmissions by the macro base stations (MBSs).
- After harvesting sufficient energy, each D2D transmitter performs spectrum sensing to opportunistically access a predefined nonexclusive D2D channel.
- Consider two different spectrum access policies for the macro BSs for their downlink transmissions - random spectrum access (RSA) and prioritized spectrum access (PSA) policies.
- D2D transmitter uses channel inversion so that the average received signal power at the intended receiver is greater than or equal to its sensitivity ρ_o.

Cognitive and energy harvesting-based D2D communictaion

- Macro BSs, cellular users, and cognitive D2D transmitters are modeled by three homogeneous PPPs: $\mathbf{\Phi}_B$, $\mathbf{\Phi}_U$, and $\mathbf{\Phi}_D$ of density λ_B, λ_U, and λ_D.
- A set of orthogonal channels $\mathcal{C} = \{c_1, c_2, \ldots, c_{|\mathcal{C}|}\}$
- All D2D transmissions take place on the same channel $c_d \in \mathcal{C}$.
- In RSA, each MBS independently and randomly uses any channel $c_i \in \mathcal{C}$ (including channel c_d) with the same probability, to serve one of its associated users.
- In PSA, each BS independently and randomly uses any channel $c_i \in \mathcal{C} \setminus \{c_d\}$ as long as the number of its associated users is less than the number of available channels $|\mathcal{C}|$.
- When the number of associated users is higher than $|\mathcal{C}| - 1$, only then the BS uses c_d.

Cognitive and energy harvesting-based D2D communictaion

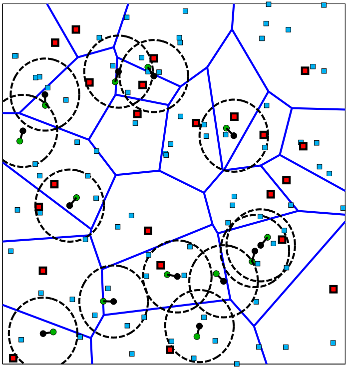
- Total power available for harvesting by a D2D transmitter located at a generic location $y \in \mathbb{R}^2$ can be expressed as

$$P_{\mathrm{H}}(y) = a \sum_{c \in \mathcal{C} \setminus \{c_d\}} \sum_{x_i \in \tilde{\mathbf{\Phi}}_B(c)} P_B h_{x_i} \|x_i - y\|^{-\alpha} \quad (2)$$

  where $\tilde{\mathbf{\Phi}}_B(c)$ is a PPP with intensity $q_c \lambda_B$ that represents the set of BSs using channel $c \in \mathcal{C} \setminus \{c_d\}$ and q_c is the probability that a BS uses this channel, $0 < a \leq 1$ is the efficiency of the conversion from RF to DC power, and $\| \cdot \|$ denotes the Euclidean distance.
- A D2D transmitter may not harvest enough energy in one time slot to transmit with sufficient power since the power available for harvesting varies depending on the location of the D2D transmitter.

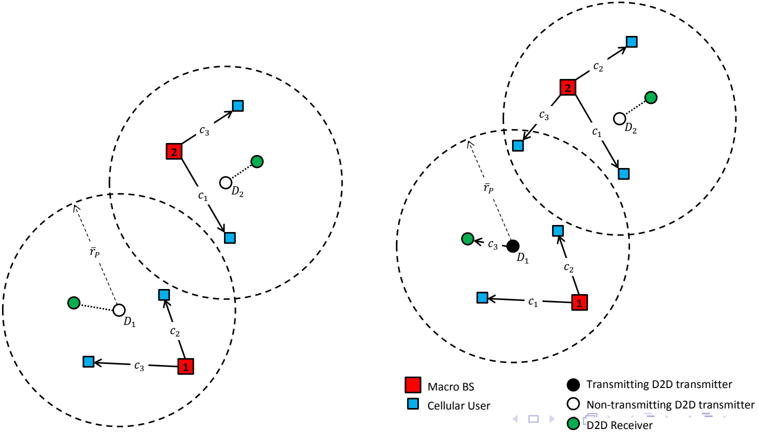
Cognitive and energy harvesting-based D2D communictaion

- Red squares represent the BS, blue squares represent the cellular users, and black lines represent the potential D2D links between the D2D transmitters (black dots) and D2D receivers (green dots). Each D2D transmitter is surrounded by a protection region $\mathcal{B}(\bar{r}_P)$ (dashed circles) with radius $\bar{r}_P$.



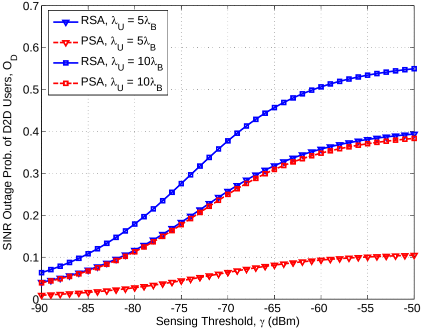
Cognitive and energy harvesting-based D2D communictaion

- RSA and PSA policies: the network consists of 2 BSs and 2 D2D transmitters, i.e., D_1 and D_2, $\mathcal{C} = \{c_1, c_2, c_3\}$ and $c_d = c_3$ (cognition with respect to MBS only).



Cognitive and energy harvesting-based D2D communictaion

- Three possible events that cause outage at a D2D receiver, i.e., the event of not harvesting sufficient energy, the event of not finding a free channel, and the event of having an insufficient SINR.

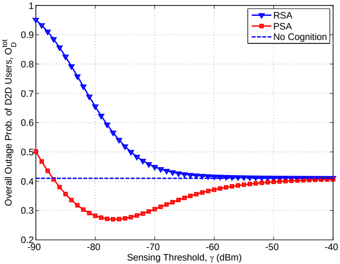


Cognitive and energy harvesting-based D2D communictaion

- For both RSA and PSA, decreasing γ improves the performance of the SINR outage probability by offering more protection for the D2D transmissions.
- The PSA policy offers a better coverage compared to the RSA policy for all values of γ.
- With PSA, the network can serve almost twice the number of cellular users that the network serves with RSA while offering the same coverage.
- The PSA policy reduces the probability of cellular users to access the D2D channel; hence, it reduces the number of active interferers on this channel, and consequently, improves the SINR.

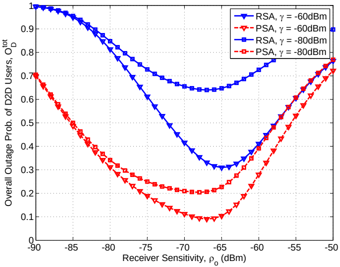
Cognitive and energy harvesting-based D2D communictaion

- Network parameters: $|\mathcal{C}| = 10$ channels, $\rho_o = -60$ dBm, $\lambda_B = 1$ BS/km^2, $\lambda_U = 5$ users/km^2, and $\lambda_D = 20$ users/km^2
- With PSA, under the same SINR outage requirements as for the case with RSA, cognition can highly improve the overall outage performance of D2D users.
- Best choice of γ is -77 dBm which offers a 150% improvement in overall outage performance compared to non-cognitive D2D transmission



Cognitive and energy harvesting-based D2D communictaion

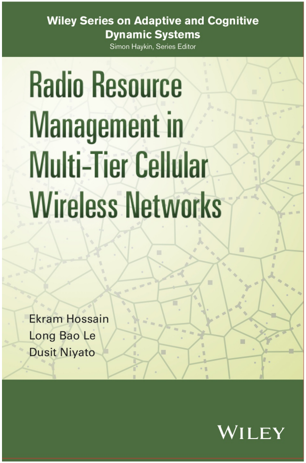
- Network parameters: $|\mathcal{C}| = 10$ channels, $\gamma = -60$ dBm, $\lambda_B = 1$ BS/km^2, $\lambda_U = 5$ users/km^2, and $\lambda_D = 20$ users/km^2
- Optimal value of ρ_0 which minimizes the overall outage probability
- For small values of ρ_0, the SINR outage probability dominates and for high values of ρ_0, the overall outage probability is dominated by the probability that a D2D transmitter fails to harvest sufficient energy to perform channel inversion.



Summary

- 5G visions and requirements
  1. Service scenarios and requirements
  2. Nevessary breakthroughs
  3. timeline
- Enabling technologies for 5G
  1. BS densification and small cells, carrier aggregation, cognitive/self-organizing small cells and D2D, network MIMO and cross-tier cooperation, cloud-RAN, inter-RAT cooperation, energy harvesting communication
- Radio resource and interference management challenges
  1. Efficient spectrum sharing among multiple network tiers, efficient techniques for carriera ggregation/bonding, optimized cell association/traffic offloading and biasing, power control, resource allocation in cloud-RAN

Book on resource management in multi-tier cellular networks



- Appendix: Poisson point process (PPP)

PPP

- PPP provides tractable results that help understanding the relationship among the performance metrics and the design parameters.
- PPP can model random network with randomized channel access.
- Provides tight bound for networks with planned deployment and networks with coordinated spectrum access.
- Most of the available literature assume that the nodes are distributed according to a PPP.
- Results obtained using PPP are accurate (within 1-2 dB) with those obtained for legacy cellular networks as well as multi-tier cellular networks.

Definition of PPP

- Let $\mathbf{\Psi} = \{x_i; i = 1, 2, 3, ...\}$ be a point process in $\mathbb{R}^d$ with intensity λ_d. Then, $\mathbf{\Psi}$ is a PPP iff
  - for any compact set $A \subset \mathbb{R}^d$, the number of points in A is a Poisson random variable
  - number of points in disjoint sets are independent.
- Number of points inside any bounded region $A \subset \mathbb{R}^d$ is given by

$$\mathbb{P}\{N(A) = k\} = \frac{\left(\lambda_d \tilde{A}\right)^k e^{-\lambda_d \tilde{A}}}{k!}$$

Important results

- **Slivnyak's theorem**: the statistics seen from a PPP is independent of the test location.
- **Campbell's theorem** (valid for a general point process): Let $g : \mathbb{R}^d \to [0, \infty)$ be a function over a point process $\boldsymbol{\Psi}$ and $\Lambda(B)$ is the intensity of the point process. Then

$$\mathbb{E}\left[\sum_{x_i \in \boldsymbol{\Psi}} g(x_i)\right] = \int_{\mathbb{R}^d} g(x)\Lambda(dx).$$

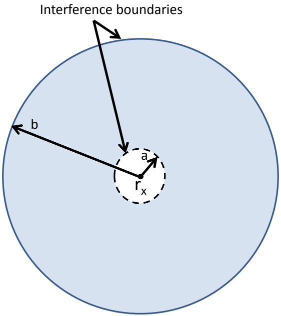
- **Probability generating functional (PGFL)**: the average of a product of a function over the point process

$$\mathbb{E}\left[\prod_{x_i \in \boldsymbol{\Psi}} g(x_i)\right] = \exp\left\{-\int_{\mathbb{R}^d} (1 - g(x))\,\Lambda(dx)\right\}.$$

LT of the *pdf* of aggregate interference

Example: For a PPP in $\mathbb{R}^2$ with density λ,

$$\mathbb{E}\left[\mathcal{I}\right] = \mathbb{E}\left[\sum_{x_i \in \boldsymbol{\Psi}} g(x_i)\right] = \mathbb{E}\left[\sum_{x_i \in \boldsymbol{\Psi}} P \left\|x_i\right\|^{-\eta}\right]$$



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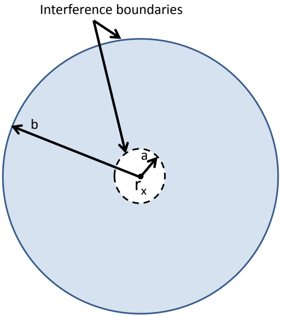
$$= \lambda \int_0^{2\pi} \int_a^b P r^{-\eta} r dr d\phi = P \frac{2\pi\lambda\left(b^{-\eta+2} - a^{-\eta+2}\right)}{2-\eta}$$



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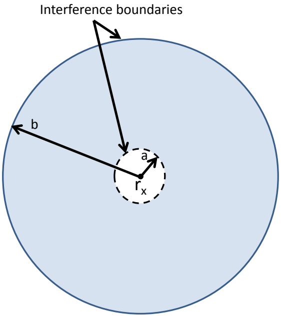

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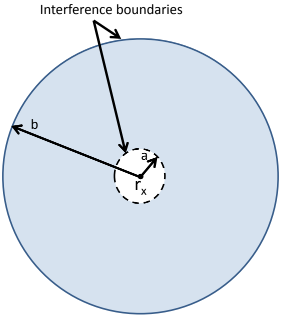

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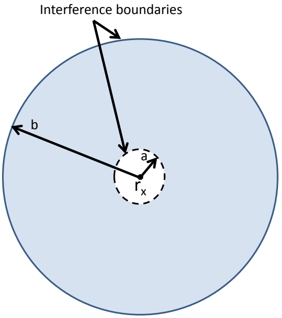

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$$= \exp\left\{-\pi\lambda\left[b^2\left(1 - e^{-sPb^{-\eta}}\right) - a^2\left(1 - e^{-sPa^{-\eta}}\right)\right.\right.$$

$$\left.\left.+(sP)^{\frac{2}{\eta}}\Gamma\left(1-\frac{2}{\eta}, sPb^{-\eta}\right) - (sP)^{\frac{2}{\eta}}\Gamma\left(1-\frac{2}{\eta}, sPa^{-\eta}\right)\right]\right\}.$$

LT of the *pdf* of aggregate interference

- For an infinite network with no receiver protection

$$\mathcal{L}_{\mathcal{I}}(s) = \exp\left\{-\pi\lambda P\Gamma\left(1-\frac{2}{\eta}\right)s^{\frac{2}{\eta}}\right\}$$

- $\mathcal{I}$ follows the α-stable distribution with *characteristic exponent* $\alpha = \frac{2}{\eta}$.
- Only moments of order lower than $2/\eta$ are finite, e.g., for $\eta > 2$, mean and variance are infinite.
- For $\eta = 4$, the *pdf* of $\mathcal{I}$ is given by:

$$f_{\mathcal{I}}(x) = \frac{\pi}{2}\lambda x^{-3/2} e^{-\frac{\pi^3\lambda^2}{4x}}.$$

Poisson field of interferers in fading channels

- For a Poisson field of interferers, the aggregate interference at the origin $\mathcal{I} = \sum_{x \in \boldsymbol{\Psi}_{\mathcal{I}}} P h_{x_i} \|x_i\|^{-\eta}$.
- **Laplace transform** of the *pdf* of $\mathcal{I}$ is

$$\mathcal{L}_{\mathcal{I}}(s) = \mathbb{E}\left[e^{-s\mathcal{I}}\right]$$

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$$= \mathbb{E}_{\mathbf{\Psi}}\left[\prod_{x \in \mathbf{\Psi}_{\mathcal{I}}} \mathcal{L}_h\left[sP||x_i||^{-\eta}\right]\right]$$

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$$\begin{aligned}
\mathcal{L}_{\mathcal{I}}(s) &= \mathbb{E}\left[e^{-s\mathcal{I}}\right] = \mathbb{E}\left[e^{-s \sum_{x \in \mathbf{\Psi}_{\mathcal{I}}} P h_{x_i} \|x_i\|^{-\eta}}\right] \\
&= \mathbb{E}_{\mathbf{\Psi}}\left[\prod_{x \in \mathbf{\Psi}_{\mathcal{I}}} \mathbb{E}_h\left[e^{-sPh_{x_i}\|x_i\|^{-\eta}}\right]\right] \\
&= \mathbb{E}_{\mathbf{\Psi}}\left[\prod_{x \in \mathbf{\Psi}_{\mathcal{I}}} \mathcal{L}_h\left[sP||x_i||^{-\eta}\right]\right] \\
&= \exp\left\{-\int_{\mathbb{R}^d \cap \mathbf{\Psi}_{\mathcal{I}}} \left(1 - \mathcal{L}_h\left(sP||\mathbf{x}||^{-\eta}\right)\right) \Lambda(d\mathbf{x})\right\}
\end{aligned}$$

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&= \exp\left\{-2\pi\lambda \int_a^{\infty} \left(1 - \mathcal{L}_h\left(sPr^{-\eta}\right)\right) rdr\right\}
\end{aligned}$$

Summary

- **Laplace transform of the pdf of interference for a PPP network***:

$$\mathcal{L}_{\mathcal{I}}(s) = e^{-\lambda\pi\left((Ps)^{\frac{2}{\eta}}\mathbb{E}\left[h^{\frac{2}{\eta}}\Gamma_L\left(1-\frac{2}{\eta},Pshr_e^{-\eta}\right)\right]-r_e^2\mathbb{E}\left[1-e^{-Pshr_e^{-\eta}}\right]\right)}$$

where $r_e = a$, $b = \infty$, and h can follow any distribution.

- For Rayleigh fading, $h \sim exp(\mu)$, and

$$\mathcal{L}_{\mathcal{I}}(s) = e^{-\pi\lambda\left((Ps)^{\frac{2}{\eta}}\mathbb{E}_h\left[h^{\frac{2}{\eta}}\Gamma_L\left(1-\frac{2}{\eta},sPhr_e^{-\eta}\right)\right]-\frac{Psr_e^2}{Ps+\mu r_e^{\eta}}\right)}.$$

- For $\eta = 4$,

$$\boxed{\mathcal{L}_{\mathcal{I}}(s) = e^{-\pi\lambda\sqrt{\frac{Ps}{\mu}}\arctan\left(\frac{\sqrt{\frac{Ps}{\mu}}}{r_e^2}\right)}.}$$

- **In general, the Laplace transform cannot be inverted to obtain the pdf of the aggregate interference.**

* M. Haenggi and R. Ganti, *Interference in Large Wireless Networks*, in *Foundations and Trends in Networking*, NOW Publishers, 2008, vol. 3, no. 2, pp. 127–248.