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# Efficient Distributed Joint Path Selection and Resource Allocation in Non-Cooperative Wireless Relay Networks

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- Introduction
- Background
- Multi-hop relaying system model
- Predicted Goodput metric for multi-hop networks
- Joint path selection (PS) and resource allocation (RA)
- Optimal centralized joint PS and RA
- Distributed joint PS and RA
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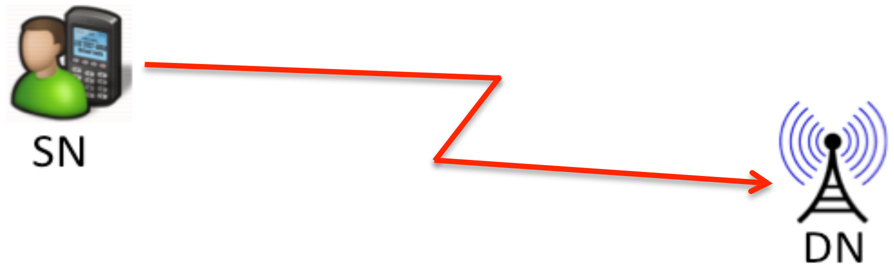
- LTE-Advanced, IEEE 802.16j WiMAX and 5G networks exploit multi-hop (MH) relaying to improve coverage, energy efficiency and battery life of devices.
- According to the MH approach, one or more relay nodes (RNs) forward information between a source node (SN) and a destination node (DN), either in cooperative mode (CM) or non-cooperative mode (NCM).
- CM relaying is more energy efficient than NCM, tough at the price of increasing processing and signaling traffic over the feedback channel.
- On the other side, in NCM, a SN transmits information passing through one or more RNs (path), while the DN receives the signal only from one RN, thus reducing processing and signaling traffic, and achieving less widespread knowledge of channel state information (CSI).
- For an efficient use of radio resources among the nodes, however, NCM requires efficient joint path selection (PS) and resource allocation (RA) techniques.

- Our aim is the design of distributed joint PS and RA for non-cooperative MH packet-oriented coded multicarrier (BIC-OFDM) wireless decode and forward (DF) relay network under outdated and imperfect CSI.
- RA means to search for the optimal transmission parameters (TPs), i.e., coding rate and bit and power loading for each relaying hop.
- PS means to search for the optimal path, i.e., the RNs connecting the SN to the DN out of the available ones.
- The joint PS and RA optimization problem (OP) adopts the Goodput (GP) as objective metric, the number of payload bits delivered in error-free packets to the end-user by unit of time (traffic offered at layer 3 of the stack).
- In order to design an efficient and distributed PS algorithm, Network Formation Game (NFG) is exploited, an effective tool formerly applied in [Li et al., IEEE INFOCOM2013] and [Saad et al., IEEE TCOM2011] yet for different contexts.

## Predicted GP metric with ideal CSI for a direct SN-DN path

- System bandwidth $B$.
- Packet payload $N_{\mathrm{p}}$.
- Coding rate $r$
- Bit loading $\mathbf{m}$ across the $N$ subcarriers.
- Transmission mode (TM) $\phi \triangleq (r, \mathbf{m})$.
- Power loading $\mathbf{p}$ across the $N$ subcarriers.
- Packet transmission time $T_{\mathrm{pkt}}(\phi) \triangleq N_u T_s / r \sum_{n=1}^{N} m_n$ .
- Packet error rate (PER) $\Phi_{\mathrm{AWGN}}(\phi, \mathbf{p})$ evaluated applying the $\kappa$-ESM method [Vandendorpe et al., IEEE TSP2012].

$$\zeta(\phi, \mathbf{p}) \triangleq \frac{1}{B} \frac{N_{\mathrm{p}}[1 - \Phi_{\mathrm{AWGN}}(\phi, \mathbf{p})]}{T_{\mathrm{pkt}}(\phi)}$$



## RA strategy for single-hop BIC-OFDM with ideal CSI

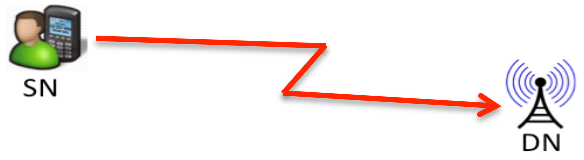
### Mixed integer OP

$$(\phi^*, \mathbf{p}^*) = \arg\max_{\phi,\mathbf{p}} \left\{ \zeta(\phi, \mathbf{p}) \right\}$$

$$\text{s.t.} \quad \sum_{n=1}^{N} p_n \le P_{\text{tot}},$$

$$p_n \ge 0, \quad 1 \le n \le N,$$

$$\phi \in D_{\text{BL}} \times D_{\text{r}}.$$

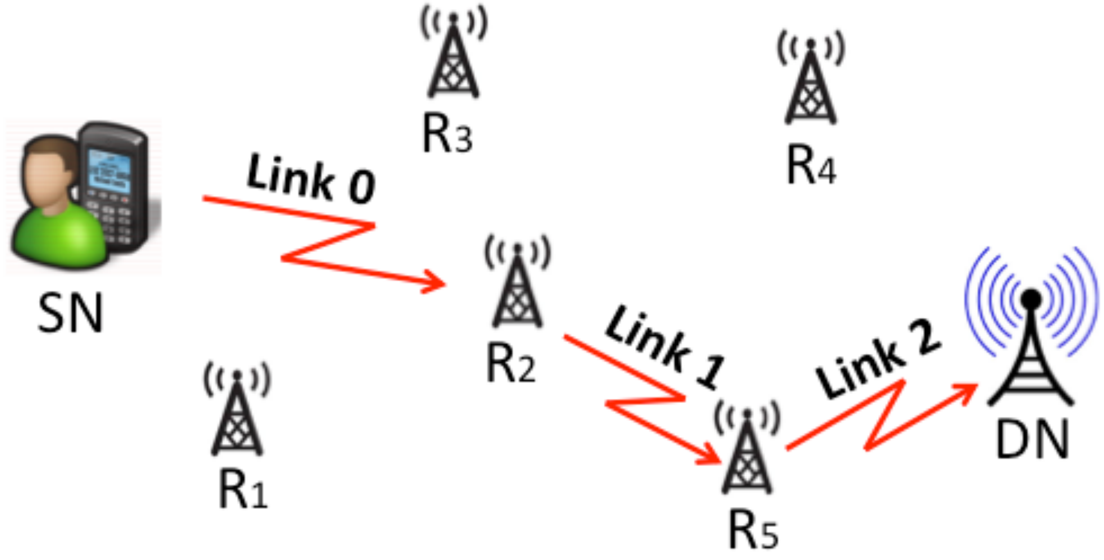



### Two step solution

1. Power allocation (PA):
   Given a generic TM $\phi$, find the best PA.
   - ✓ The OP is convex.
   - ✓ The best PA is found applying the Lagrange dual decomposition (LDD) with KKT conditions.
   - ✓ The closed-form optimal solution $\mathbf{p}^*(\phi)$ depends only on the TM $\phi$.

2. Bit allocation and coding rate (TM):
   - ✓ Uniform bit loading: exhaustive search
   - ✓ Optimal bit loading: greedy algorithm

- Fixed or mobile SN, DN and $M$ RNs.
- DF relaying.
- BIC-OFDM scheme for each node.
- For the $l$-th link:
  - Encoding with rate $r_l \in D_{\mathrm{r}}$;
  - Bit loading $\mathbf{m}_l \triangleq [m_{l,1}, \cdots, m_{l,N}]^{\mathrm{T}}$ across the $N$ subcarriers, with $m_{l,n} \in D_{\mathrm{m}} \triangleq \{0, 2, 4, \cdots, m_{\max}\}$ being the number of bits allocated on the $n$-th subcarrier;
  - Power loading $\mathbf{p}_l \triangleq [p_{l,1}, \cdots, p_{l,N}]^{\mathrm{T}}$ across the $N$ subcarriers;
  - At the receiver side, estimation $\hat{\mathbf{H}}_l \triangleq [\hat{H}_{l,1}, \cdots, \hat{H}_{l,N}]^{\mathrm{T}}$ of the actual channel.

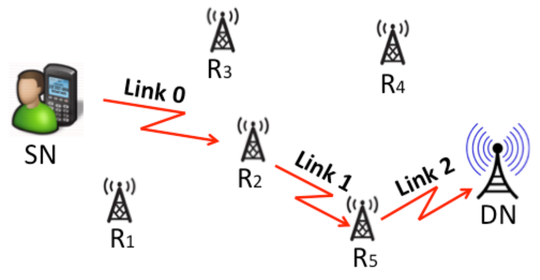


## Predicted GP (PGP) metric for MH network with imperfect and outdated CSI for a SN-DN path

- TM for the $l$-th link: $\phi_l \triangleq \{r_l, \mathbf{m}_l\} \in D_{\mathrm{BL}} \times D_{\mathrm{r}}$.
- $\Phi_{\mathrm{tot}}(r_0,\cdots,r_L,\gamma_{0,\mathrm{eff}},\cdots,\gamma_{L,\mathrm{eff}})$ is the PER for a path from SN to DN using $L \le M$ RNs.
- The PER of the $i$-th link $\Phi_i(r_i,\gamma_{i,\mathrm{eff}})$ is evaluated applying a modified version of the $\kappa$-ESM method as a function of the equivalent SNR $\gamma_{i,\mathrm{eff}}$.
- The modified method takes account of the imperfect and outdated CSI due to non ideal estimation at the receiver and delay over the feedback channel [Van Hecke et al., EURASIP JWCN2016].

$$\zeta_{\mathrm{global}}(\phi_0,\cdots,\phi_L,\mathbf{p}_0,\cdots,\mathbf{p}_L) = \frac{1}{B}\frac{N_{\mathrm{p}}[1-\Phi_{\mathrm{tot}}(r_0,\cdots,r_L,\gamma_{0,\mathrm{eff}},\cdots,\gamma_{L,\mathrm{eff}})]}{\sum_{j=0}^{L} T_{\mathrm{pkt},j}(\phi_j)}$$

$$\Phi_{\mathrm{tot}}(r_0,\cdots,r_L,\gamma_{0,\mathrm{eff}},\cdots,\gamma_{L,\mathrm{eff}}) \cong \sum_{i=0}^{L} \Phi_i(r_i,\gamma_{i,\mathrm{eff}})$$



# Optimal centralized joint PS and RA with non ideal CSI 1/2

## Mixed integer OP

$$\forall L \le M$$

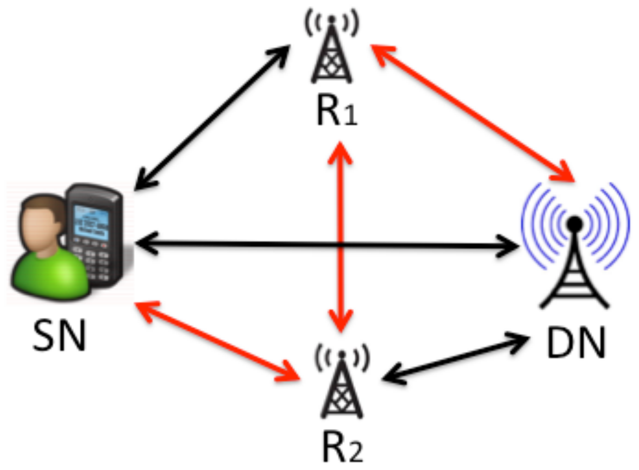
$$(\phi_0^*, \cdots, \phi_L^*, \mathbf{p}_0^*, \cdots, \mathbf{p}_L^*) = \underset{\phi_0,\cdots,\phi_L,\mathbf{p}_0,\cdots,\mathbf{p}_L}{\arg\max} \left\{ \zeta_{\text{global}}(\phi_0,\cdots,\phi_L,\mathbf{p}_0,\cdots,\mathbf{p}_L) \right\}$$

$$\text{s.t.} \quad \sum_{n=1}^{N} p_{l,n} \le P_{\text{tot}}, \quad 0 \le l \le L,$$

$$p_{l,n} \ge 0, \quad 0 \le l \le L, 0 \le n \le N,$$

$$\phi_l \in D_{\text{BL}} \times D_{\text{r}}, \quad 0 \le l \le L.$$

- The DN is assumed as a centralized processing unit which loads all the computational complexity.
- The DN performs exhaustive search over any possible SN-DN path through some RNs to optimize the PGP.



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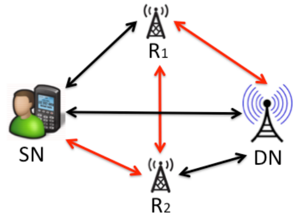
# Optimal centralized joint PS and RA with non ideal CSI 2/2

## Multi step solution

- **Step 1: Per-path PGP evaluation**
  For every path, the DN collects the predicted channels and find the TPs optimizing the PGP.
  - ✓ Step 1.1, PA evaluation: given a generic TM, the best PA is found solving a convex OP which yields a water-filling like solution depending on the BL only.
  - ✓ Step 1.2, TM evaluation: given the closed form of the PA found in Step 1.1, the best TM is selected applying exhaustive search (uniform BL) or greedy search (optimal BL).
- **Step 2: Best path selection**
  The DN selects the path giving the maximum PGP and sends the optimal TPs to the SN and RNs belonging to the selected path.

- $M!/(M-L)!$ SN-DN paths through $L \leq M$ RNs.
- Exhaustive search over all the possible paths needs combinatorial complexity.
- The DN receives the CSI from any link of the network, and then, it sends the optimal TPs to the nodes belonging to the selected path, thus giving rise to congestion of the feedback channel.
- Due to the unfeasible complexity is is considered as benchmark only.



# Distributed joint PS and RA with non ideal CSI 1/3

- The distributed joint PS and RA strategy is derived by formalizing the problem in the NFG framework.
- The network topology is described by a direct graph, i.e., a set of all vertices (RNs) and the set of the links among RNs.
- The SN is an external source of traffic and access the network only when the topology is optimized, thus reducing the waiting time to start its transmission and the signaling traffic.
- The RN-based NFG is defined by the triplet:
- The *best feasible* strategy if

$$\mathcal{U}_{R_k}(S^*_{R_k}, S_{-R_k}) \geq \mathcal{U}_{R_k}(S_{R_k}, S_{-R_k}), \forall S_{R_k} \in \overline{S}_{R_k},$$

where $\overline{S}_{R_k}$ is the set of the feasible strategies and $S^*_{R_k} \triangleq \{\mathcal{P}^*_{R_k}, \phi^*_{R_k}, \mathbf{p}^*_{R_k}\}$ is the *best response* (BR) of the NFG optimizing the utility function.

✓ The set of RNs (the *players*) $\mathcal{R} \triangleq \{R_1, \cdots, R_M\}$ .

✓ The set of *strategies* $\mathcal{S} \triangleq \{S_{R_1}, \cdots, S_{R_M}\}$ with $S_{R_k} \triangleq \{\mathcal{P}_{R_k}, \phi_{R_k}, \mathbf{p}_{R_k}\}$, being $\mathcal{P}_{R_k} \in \mathcal{G}_{R_k}$ the path connecting $R_k$ and DN, the pair code rate and bit loading, and the power loading, respectively.

✓ The set of the *utility function* $\mathcal{U} \triangleq \{\mathcal{U}_{R_1}, \cdots, \mathcal{U}_{R_M}\}$ ,where

$$\mathcal{U}_{R_k}(S_{R_k}, S_{-R_k}) \triangleq \frac{1}{B} \frac{N_p[1-\tilde{\Phi}_{tot}(S_{R_k}, S_{-R_k})]}{\tilde{T}^{(tot)}_{pkt}(S_{R_k}, S_{-R_k})},$$

being $S_{-R_k}$ the of strategies of all the RNs except $R_k$, $\tilde{\Phi}_{tot}(S_{R_k}, S_{-R_k})$ the PER of $R_k$-DN, and $\tilde{T}^{(tot)}_{pkt}(S_{R_k}, S_{-R_k})$ the packet delivery time.

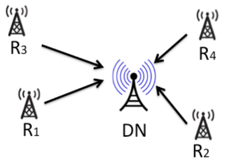
# Distributed joint PS and RA with non ideal CSI 2/3

The RN-based NFG is solved by a two-step method:

- Step 1. The BR $S^*_{\mathrm{R}_k} = \underset{S_{\mathrm{R}_k} \in \bar{S}_{\mathrm{R}_k}}{\operatorname{argmax}} \left\{ \mathcal{U}_{\mathrm{R}_k}(S_{\mathrm{R}_k}, S_{-\mathrm{R}_k}) \right\}$ problem is iteratively solved for each RN $\mathrm{R}_k$, where each iteration consists of three tasks. The iterations end when an equilibrium point is reached, the Nash network, i.e., when any $\mathrm{R}_k$ has no incentive to change its strategy $S_{\mathrm{R}_k}$ to improve its utility function $\mathcal{U}_{\mathrm{R}_k}$.

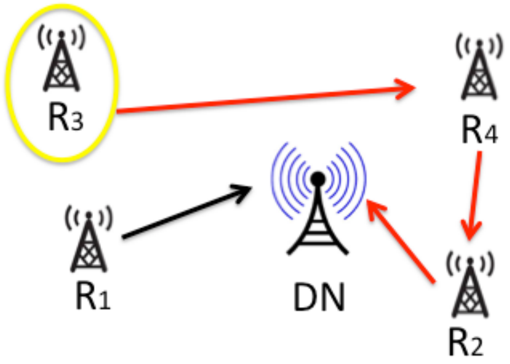
- Step 2. Once a final topology is built (for each $\mathrm{R}_k$, the optimal path $\mathcal{P}^*_{\mathrm{R}_k}$ connecting $\mathrm{R}_k$ to DN and the optimal TPs of the links belonging to $\mathcal{P}^*_{\mathrm{R}_k}$), the SN can access the network by selecting the final path SN-DN $\mathcal{P}^*_{\mathrm{S}}$, the best TM $\phi^*_0$ and the best power loading $\mathbf{p}^*_0$ that optimize the global PGP.

Initialization: RNs directly connected to the DN (star topology network).




$N_{\mathrm{NFG}}$

1. Each RN $\mathrm{R}_k$ evaluates the feasible strategy $\bar{S}_{\mathrm{R}_k}$, given $\bar{S}_{-\mathrm{R}_k}, \forall k \in \{1, \cdots, M\}$.
2. The BR $S^*_{\mathrm{R}_k} \in \bar{S}_{\mathrm{R}_k}, \forall k \in \{1, \cdots, M\}$, is selected and sent to the DN.
3. At the end of iterations, the DN broadcasts the selected BRs to all the RNs.



# Distributed joint PS and RA with non ideal CSI 3/3

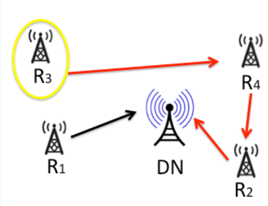
## Iteration 1. of Step 1. for the RN-based NFG

- $\forall \mathcal{P}_{\mathrm{R}_k} \in \mathcal{G}_{\mathrm{R}_k}$ ($\mathcal{G}_{\mathrm{R}_k}$ is the set of all the paths between $\mathrm{R}_k$ and DN), each RN $\mathrm{R}_k$ builds the set $\bar{S}_{\mathrm{R}_k}$ (set of feasible strategies) given $\bar{S}_{-\mathrm{R}_k}$ by evaluating its TP over the first hop and collecting any $S_{\mathrm{R}_k}$ such that $\mathcal{U}_{\mathrm{R}_k}(S_{\mathrm{R}_k}, S_{-\mathrm{R}_k}) > 0$. Instead of applying exhaustive search over $\mathcal{G}_{\mathrm{R}_k}$, it has to be noted that adopting the modified Bellman-Ford algorithm gives a suboptimal yet practical solution with complexity $\mathcal{O}(M^3)$, i.e., not combinatorial in the number of RNs.
- For each RN, the OP to evaluate the TPs over every $\mathcal{P}_{\mathrm{R}_k} \in \mathcal{G}_{\mathrm{R}_k}$ is similar to that of the centralized case, but now the difference is that the optimization variables are only $(\phi_{\mathrm{R}_k}, \mathbf{p}_{\mathrm{R}_k})$.
- Given a generic path $\mathcal{P}'_{\mathrm{R}_k}(\mathrm{R}_k, \mathrm{R}_{i_1}, \cdots, \mathrm{R}_{i_L}, \mathrm{DN}) \in \mathcal{G}_{\mathrm{R}_k}$ and the set of strategies $S_{-\mathrm{R}_k}$ of the other RNs belonging to $\mathcal{P}'_{\mathrm{R}_k}$, the TPs are found by solving the OP

$$(\phi^*_{\mathrm{R}_k}, \mathbf{p}^*_{\mathrm{R}_k}) = \arg\max_{\phi_{\mathrm{R}_k}, \mathbf{p}_{\mathrm{R}_k} \geq 0} \left\{ \mathcal{U}_{\mathrm{R}_k}(\mathcal{P}'_{\mathrm{R}_k}, \phi_{\mathrm{R}_k}, \mathbf{p}_{\mathrm{R}_k}, S_{-\mathrm{R}_k}) \right\}$$
$$\text{s.t.} \quad \sum_{n=1}^{N} p_{\mathrm{R}_k,n} \leq P_{\mathrm{tot}}, \phi_{\mathrm{R}_k} \in D_{\mathrm{BL}} \times D_{\mathrm{r}}.$$

- The optimal power loading $\mathbf{p}^*_{\mathrm{R}_k}(\mathbf{m}_{\mathrm{R}_k})$ is a closed-form water-filling like solution depending on the BL only. Then, the optimal TM (coding rate and BL) is evaluated by solving the OP

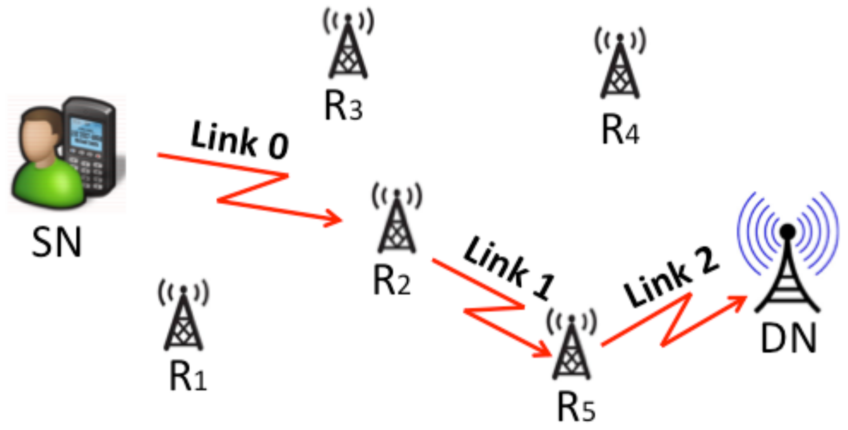
$$\phi^*_{\mathrm{R}_k} = \arg\max_{\phi_{\mathrm{R}_k}} \left\{ \mathcal{U}_{\mathrm{R}_k}(\mathcal{P}'_{\mathrm{R}_k}, \phi_{\mathrm{R}_k}, \mathbf{p}^*_{\mathrm{R}_k}(\mathbf{m}_{\mathrm{R}_k}), S_{-\mathrm{R}_k}) \right\} \quad \text{s.t.} \quad \phi_{\mathrm{R}_k} \in D_{\mathrm{BL}} \times D_{\mathrm{r}}.$$




The TM solution is given by exhaustive search over $D_{\mathrm{BL}} \times D_{\mathrm{r}}$ for uniform BL or by the greedy algorithm for optimal BL.

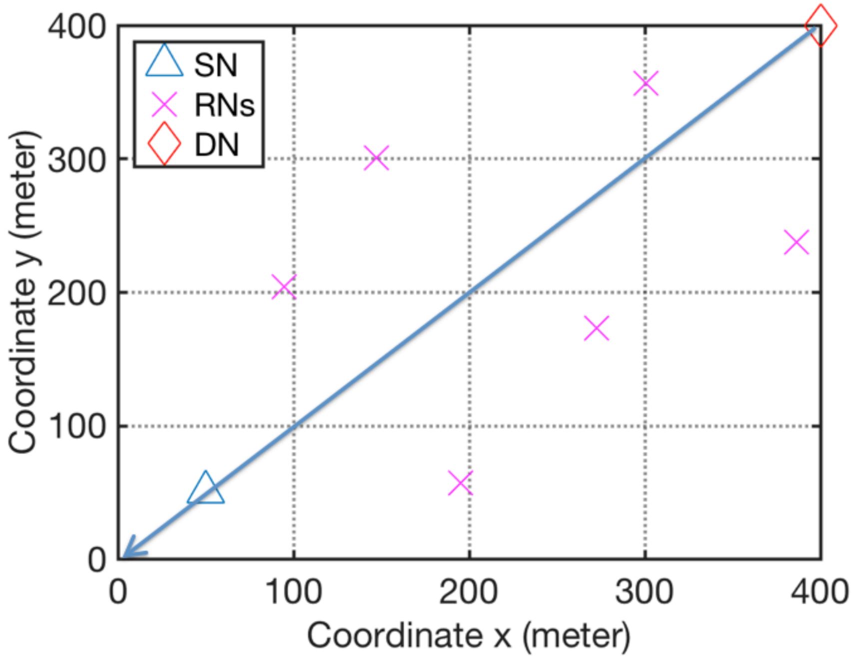
# Simulation set-up

- Averaged GP (AGP) as performance metric measured by averaging the number of payload bits error-free received over $N_{\mathrm{pkt}} = 1000$ transmitted packets, normalized by unit of time and bandwidth (bits/s/Hz)
- Number of information bits $N_{\mathrm{p}} = 1024$
- Number of CRC bits $N_{\mathrm{CRC}} = 32$
- Number of subcarriers $N = 1320$ and FFT size $N_{\mathrm{FFT}} = 2048$
- Bandwidth $B = 20$ MHz
- Modulation set $\mathcal{D}_{\mathrm{m}} = \{2,4,6\}$
- Convolutional code with coding rate set $\mathcal{D}_{\mathrm{r}} = \{1/2, 2/3, 3/4, 5/6\}$
- Modified COST231 Hata path loss (PL) model with Doppler frequency $f_{\mathrm{d}} = 144$ Hz
- For all the nodes $P_{\mathrm{tot}} = 25$ dBm
- In-band power noise level $-100$ dBm
- Number of NFG iterations $N_{\mathrm{NFG}} = 6$
- Minimum distance among nodes $d_{\mathrm{min}} = 80$ m

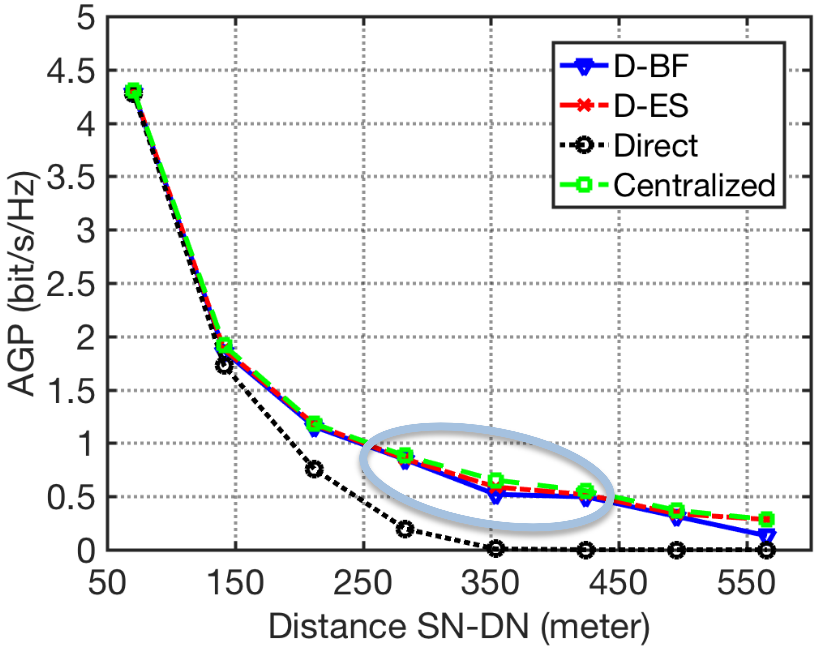


# Simulation results 1/2

Network scenario with:
- $M = 6$ fixed RNs
- SN moving away from DN
- Fixed DN

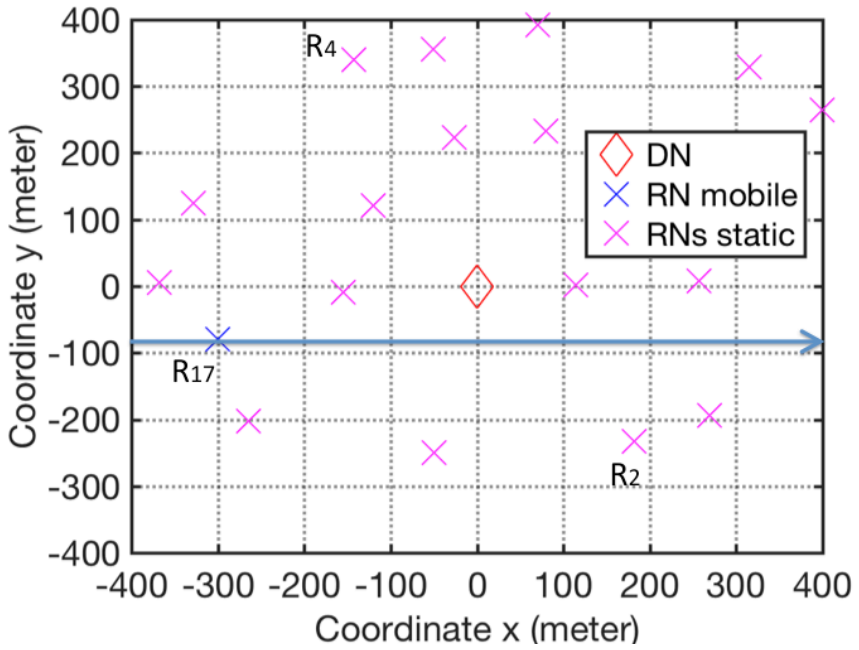



AGP performance vs. SN-DN distance for algorithms:
- Optimal centralized
- Direct SN-DN link
- Distributed NFG with exhaustive search (D-ES)
- Distributed NFG with modified Bellman-Ford (D-BF)

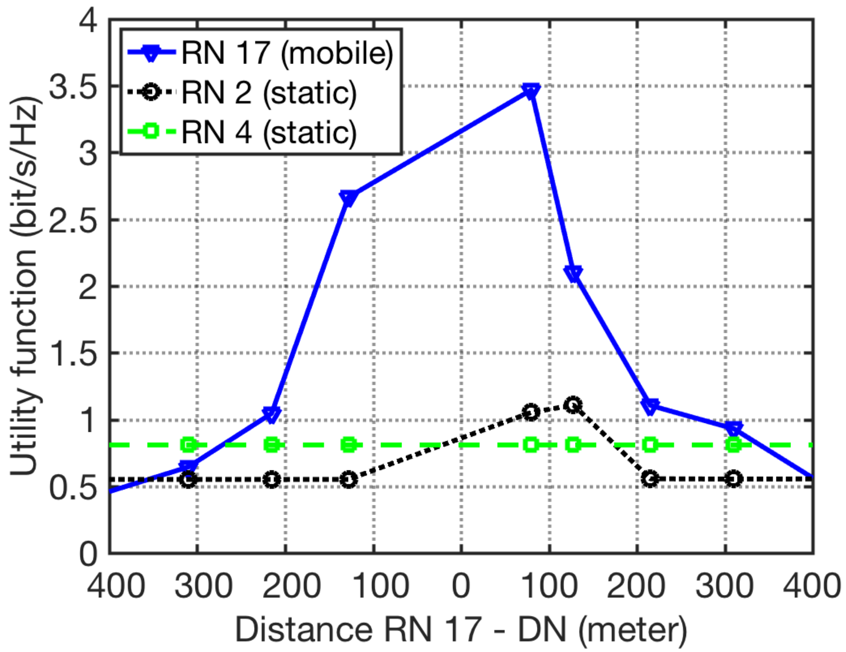


# Simulation results 2/2

Network scenario with:
- $M = 18$ RNs with only $R_{17}$ moving horizontally
- Fixed DN




NFG utility functions vs. $R_{17}$-DN distance for:
- Mobile $R_{17}$
- Fixed $R_2$
- Fixed $R_4$




- ✓ While $R_2$ changes its strategy $S_{R_2}$ when $R_{17}$ is close to it, $R_4$ and $R_{17}$ have no incentive to cooperate together
- ✓ When a RN is moving, the network can adapt itself and the NFG converges to an equilibrium point where the RNs have no incentive to change their strategies

- The following joint PS and RA strategies are proposed as novel solutions to optimize the SN-DN GP metric for a DF relaying network employing BIC-OFDM under outdated and imperfect CSI.

  1) The centralized solution which exhibits unfeasible computational complexity, and as such, it is adopted as benchmark case.

  2) The NFG-based distributed solution which significantly reduces the signaling traffic among nodes.

  3) The NFG-based distributed solution exploiting the modified Bellman-Ford algorithm which allows to decrease the computational load for each node from combinatorial to a polynomial one in the number of RNs.

- Simulation results show that the distributed strategies offer GP performance very close to the centralized benchmark case, but with a considerable reduction of both signaling and computational complexity.

## Acknowledgement

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