Space-Time Power Scheduling – From Wireless Intranet to Wireless Internet

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What is Space-Time Power Scheduling

- It is about the distribution of transmitted power in a wireless network over space, time and frequency.
- The space refers to node locations, transmit antennas and transmit beams.
- The time and frequency may be within or beyond channel coherence time and bandwidth.

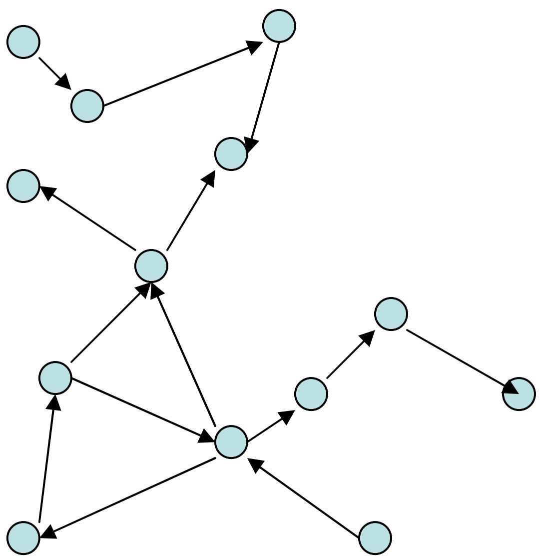
Why is Space-Time Power Scheduling

- It sets an upper limit on the network throughput, achievable by the best choice of coding, modulation and channel estimation schemes.
- It is a useful approach to maximizing the network throughput for any *given* coding, modulation and channel estimation schemes.

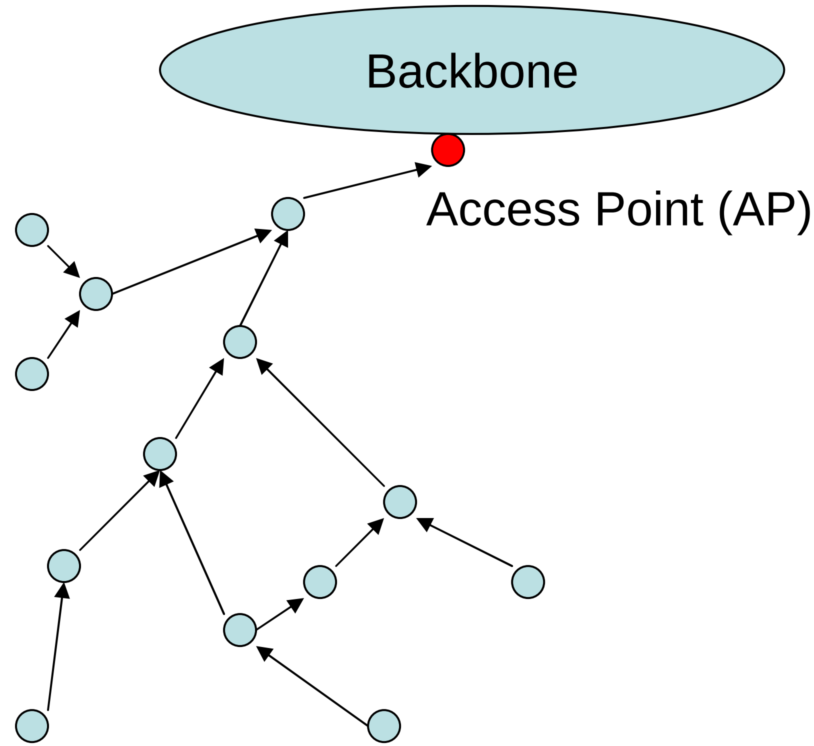
How to do Space-Time Power Scheduling

- It depends:
  - Various constraints on peak power, average power, computational capability, centralization, decentralization, mobility, time scale, channel state information, etc.
  - Large network of many nodes
  - Small network of a few nodes
  - To maximize the *intranet* throughput
  - To maximize the *internet* throughput

Intranet Traffic versus Internet Traffic



Data flows within the network



Data flows to or from the AP

What We Have Done

- Synchronous array methods for *intranet* traffic in large-scale wireless networks (5 journal papers and 4 conference papers).
- Space-time power scheduling for *intranet* traffic in random networks of MIMO links (3 journal papers and 3 conference papers).
- Space-time power scheduling for wireless *internet* traffic (publication under preparation).

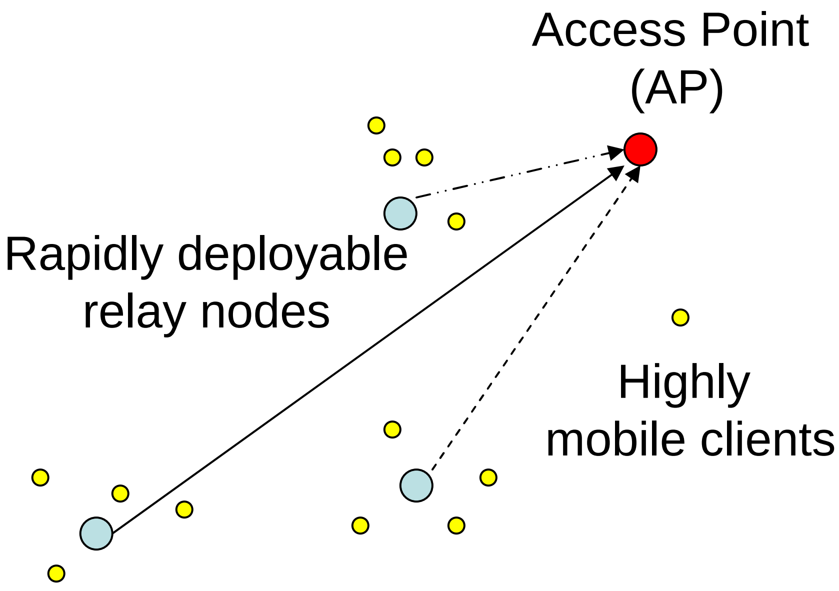
Wireless Internet Traffic

- Existing Schemes.
- A New Scheme – Dirty paper coding (DPC) assisted multihop.

Existing Schemes

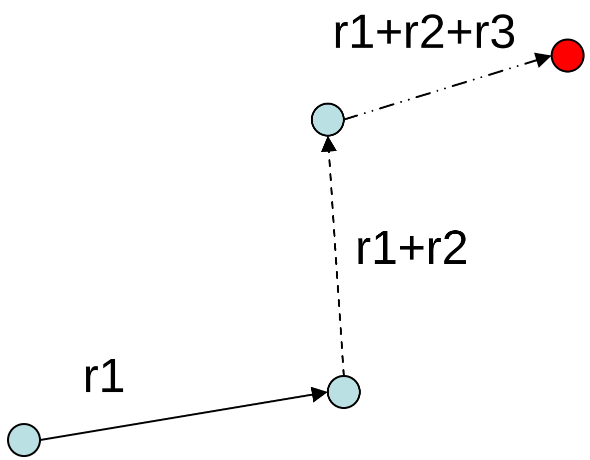
(“Uplink” only in these slides)

- Direct Access (DA):



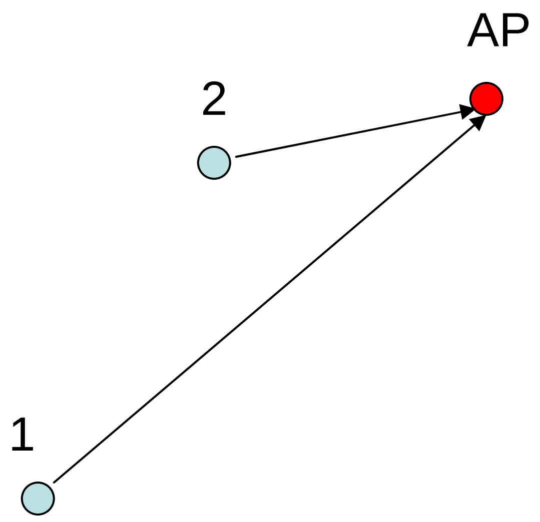
Disadvantage: the <u>far away relay nodes</u> can be overly burdened.

- Nearest Neighbor (NN) Hopping:



Disadvantage: the <u>relay nodes close to AP</u> can be overly burdened

- Successive Interference Cancellation (SIC) assisted Direct Access (DA):



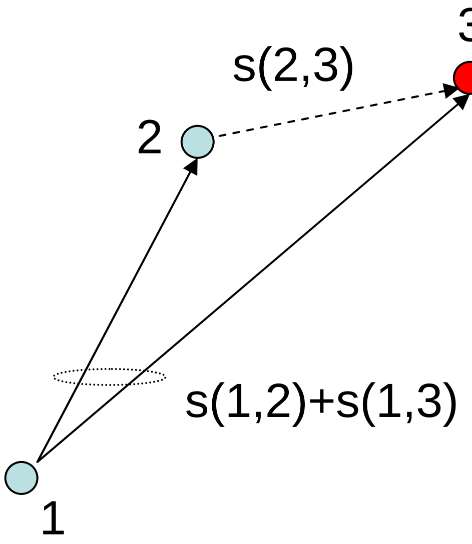
$$r_i \le \log_2\left(1+\frac{|h_i|^2 P_i}{\sigma^2}\right), \quad i=1,2$$

$$r_1+r_2 \le \log_2\left(1+\frac{|h_1|^2 P_1}{\sigma^2}\right)+\log_2\left(1+\frac{|h_2|^2 P_2}{\sigma^2+|h_1|^2 P_1}\right)$$

$$=\log_2\left(1+\frac{|h_1|^2 P_1+|h_2|^2 P_2}{\sigma^2}\right)$$

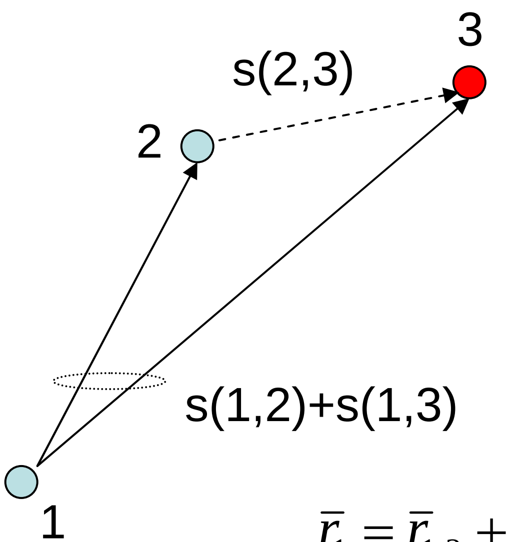
1. All nodes transmit to AP at the same time and same frequency.
2. AP uses SIC for multiuser detection.
3. This scheme is optimal in sum rate.
4. But it suffers the same problem as the previous DA scheme, i.e., the far away nodes are disadvantaged.

The New Scheme – DPC assisted Multihop



- In channel 1, node 1 transmits s(1,2) + s(1,3) to both nodes 2 and 3.
  - ✓ Node 3 decodes s(1,3) with s(1,2) as interference.
  - ✓ Node 2 decodes s(1,2) with s(1,3) virtually cancelled due to DPC.
- In channel 2, node 2 transmits s(2,3) to node 3.
- s(2,3) carries the information originally from node 2 and the information extracted from s(1,2).
- Clearly, the DA and NN schemes are special cases.
- We use two channels since we do not consider unrealistic “full duplex relay”.

The New Scheme – DPC assisted Multihop



- The data rates from nodes 1 and 2, in bits/s/Hz averaged over two equal channels, are shown below.
- The factor ½ accounts for the use of two channels.

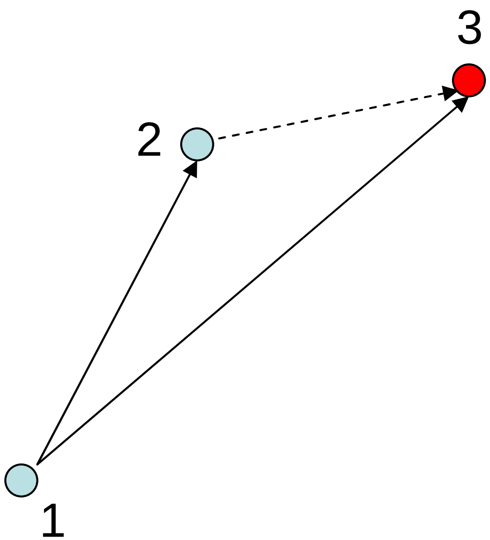
$$\bar{r}_1 = \bar{r}_{1,2} + \bar{r}_{1,3} = \frac{1}{2}\log_2\left(1+\frac{|h_{1,2}|^2 P_{1,2}}{\sigma^2}\right) + \frac{1}{2}\log_2\left(1+\frac{|h_{1,3}|^2 P_{1,3}}{\sigma^2 + |h_{1,3}|^2 P_{1,2}}\right)$$

$$\bar{r}_2 = \bar{r}_{2,3} - \bar{r}_{1,2} = \frac{1}{2}\log_2\left(1+\frac{|h_{2,3}|^2 P_{2,3}}{\sigma^2}\right) - \frac{1}{2}\log_2\left(1+\frac{|h_{1,2}|^2 P_{1,2}}{\sigma^2}\right)$$

$$P_{1,2} + P_{1,3} = 2\overline{P}_1$$

$$P_{2,3} = 2\overline{P}_2$$

Comparing Two Alternatives of DPC-Multihop



Theorem: Scheme A has a higher capacity than Scheme B if

$$|h_{1,2}| > |h_{1,3}| \; .$$

We will refer to Scheme A as DPC-Multihop.

Scheme A: Interference is cancelled at node 2:

$$\bar{r}_1^A = \bar{r}_{1,2}^A + \bar{r}_{1,3}^A = \frac{1}{2}\log_2\left(1+\frac{|h_{1,2}|^2 P_{1,2}^A}{\sigma^2}\right) + \frac{1}{2}\log_2\left(1+\frac{|h_{1,3}|^2 P_{1,3}^A}{\sigma^2 + |h_{1,3}|^2 P_{1,2}^A}\right)$$

$$\bar{r}_2^A = \bar{r}_{2,3}^A - \bar{r}_{1,2}^A = \frac{1}{2}\log_2\left(1+\frac{|h_{2,3}|^2 P_{2,3}^A}{\sigma^2}\right) - \frac{1}{2}\log_2\left(1+\frac{|h_{1,2}|^2 P_{1,2}^A}{\sigma^2}\right)$$

$$P_{1,2}^A + P_{1,3}^A = 2\overline{P}_1 \quad P_{2,3}^A = 2\overline{P}_2$$

Scheme B: Interference is cancelled at node 3:

$$\bar{r}_1^B = \bar{r}_{1,2}^B + \bar{r}_{1,3}^B = \frac{1}{2}\log_2\left(1+\frac{|h_{1,2}|^2 P_{1,2}^B}{\sigma^2 + |h_{1,2}|^2 P_{1,3}^B}\right) + \frac{1}{2}\log_2\left(1+\frac{|h_{1,3}|^2 P_{1,3}^B}{\sigma^2}\right)$$

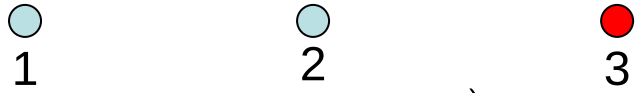
$$\bar{r}_2^B = \bar{r}_{2,3}^B - \bar{r}_{1,2}^B = \frac{1}{2}\log_2\left(1+\frac{|h_{2,3}|^2 P_{2,3}^B}{\sigma^2}\right) - \frac{1}{2}\log_2\left(1+\frac{|h_{1,2}|^2 P_{1,2}^B}{\sigma^2 + |h_{1,2}|^2 P_{1,3}^B}\right)$$

$$P_{1,2}^B + P_{1,3}^B = 2\overline{P}_1, \quad P_{2,3}^B = 2\overline{P}_2$$

Comparing DPC-Multihop with SIC-DA

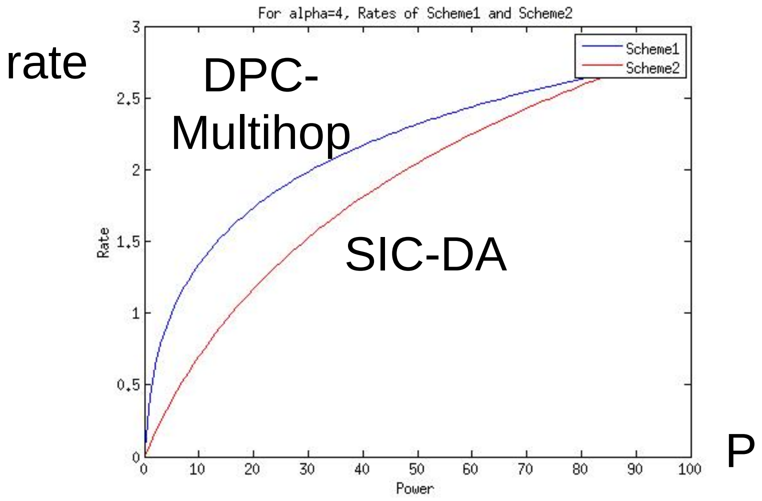
Assume that each node consumes the same <u>averaged power P</u> and

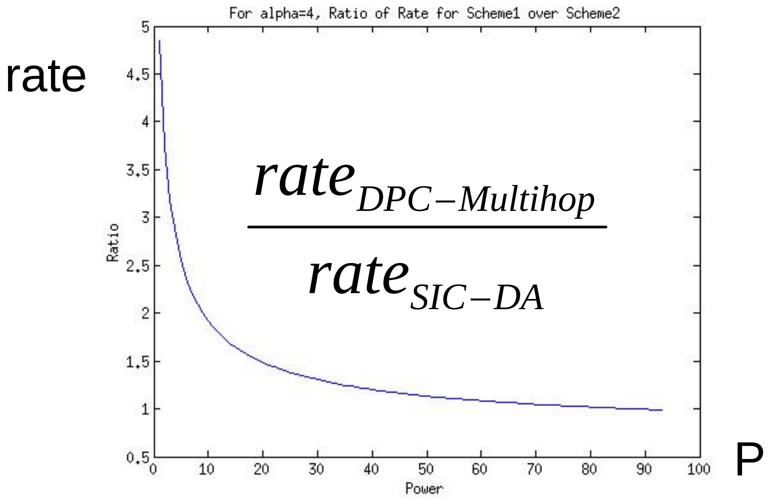
$$|h_{1,2}| = |h_{2,3}| = 1, \quad |h_{1,3}|^2 = 2^{-\alpha}, \quad \alpha = 4, \quad \sigma^2 = 1$$



$$rate_{DPC-Multihop} = \max \min \left(\bar{r}_1^{DPC-Multihop}, \bar{r}_2^{DPC-Multihop} \right)$$

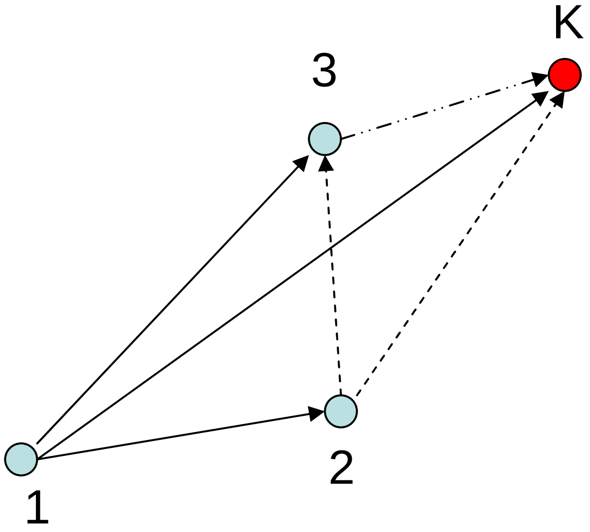
$$rate_{SIC-DA} \hat{=} \max \min \left(\bar{r}_1^{SIC-DA}, \bar{r}_2^{SIC-DA} \right)$$





DPC-Multihop has a <u>higher maxmin capacity</u> than SIC DA in the low power region (i.e., when nominal SNR = P is less than 90 in this case).

The DPC-Multihop Scheme for K nodes



$$r_i = (K-1)\bar{r}_i \le \sum_{j=i+1}^{K} r_{i,j} - \sum_{m=1}^{i-1} r_{m,i}, i = 1, 2, \cdots, K-1$$

$$r_{i,j} = (K-1)\bar{r}_{i,j} = \log_2\left(1 + \frac{\left|h_{i,j}\right|^2 P_{i,j}}{\sigma^2 + \left|h_{i,j}\right|^2 \sum_{m=i+1}^{j-1} P_{i,m}}\right)$$

$$P_i = (K-1)\overline{P_i} = \sum_{j=i+1}^{K} P_{i,j}$$

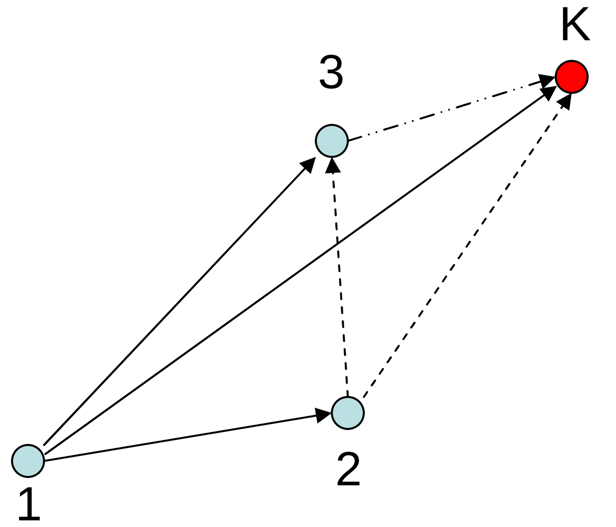
1. The factor 1/(K-1) is consistent with the optimal scaling law.
2. Given the DPC-Multihop framework, there are a number of ways to design the space-time power scheduling, which will be illustrated later.

The DPC-Multihop Scheme for MIMO nodes

$$r_i \le \sum_{j=i+1}^{K} r_{i,j} - \sum_{m=1}^{i-1} r_{m,i}, i = 1,2,\cdots,K-1$$

$$r_{i,j} = \log_2 \det\left(\mathbf{I} + \mathbf{H}_{i,j}\mathbf{P}_{i,j}\mathbf{H}_{i,j}^H \left(\mathbf{I} + \mathbf{H}_{i,j} \sum_{m=i+1}^{j-1} \mathbf{P}_{i,m}\mathbf{H}_{i,j}^H \right)^{-1} \right)$$

$$P_i = \sum_{j=i+1}^{K} P_{i,j} = \sum_{j=i+1}^{K} Tr\left(\mathbf{P}_{i,j}\right)$$



Using successive water filling, we can write a closed-form one-to-one function between

$\{r_{i,j}\}$ and $\{P_{i,j}\}$

A Useful Property

We can write $r_i \leq \sum_{j=i+1}^{K} r_{i,j} - \sum_{m=1}^{i-1} r_{m,i}, i = 1,2,\cdots,K-1$ as $\mathbf{r} \leq \mathbf{A}_K \mathbf{x}$ where

$$\mathbf{r} = \begin{bmatrix} r_1 & r_2 & \cdots & r_{K-1} \end{bmatrix}^T$$

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}_1{}^T & \mathbf{x}_2{}^T & \cdots & \mathbf{x}_{K-1}{}^T \end{bmatrix}$$

$$\mathbf{x}_i = \begin{bmatrix} r_{i,i+1} & r_{i,i+2} & \cdots & r_{i,K} \end{bmatrix}^T$$

$$\mathbf{A}_K \mathbf{A}_K{}^T = \begin{bmatrix} K-1 & -1 & \cdots & -1 \\ -1 & K-1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & -1 \\ -1 & \cdots & -1 & K-1 \end{bmatrix} = K\mathbf{I} - \mathbf{1}\mathbf{1}^T$$

$$\mathbf{A}_3 = \begin{bmatrix} 1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

$$\left(\mathbf{A}_K \mathbf{A}_K{}^T\right)^{-1} = \frac{1}{K} \begin{bmatrix} 2 & 1 & \cdots & 1 \\ 1 & 2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 1 \\ 1 & \cdots & 1 & 2 \end{bmatrix} = \frac{1}{K}\left(\mathbf{1}\mathbf{1}^T + \mathbf{I}\right)$$

$$\mathbf{A}_k = \left[\begin{array}{cccc|c} 1 & \cdots & \cdots & 1 & 0 \\ \hline -1 & & & 0 & \\ & \ddots & & \vdots & \mathbf{A}_{k-1} \\ & & -1 & 0 & \end{array}\right]$$

$$(k-1) \times \frac{k(k-1)}{2}$$

This property is very useful for fast computations.

Another Useful Property

Given $\mathbf{A}_K$, we define:

$$\mathbf{S}_3{}^T = \begin{bmatrix} 1 & -1 & 1 \end{bmatrix} \qquad \mathbf{S}_4{}^T = \begin{bmatrix} 0 & 0 & 0 & 1 & -1 & 1 \\ 1 & -1 & 0 & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 & 1 & 0 \end{bmatrix}$$

$$\mathbf{S}_k{}^T = \left[\begin{array}{c|c} \mathbf{0}_{\frac{(k-2)(k-3)}{2}\times(k-1)} & \mathbf{S}_{k-1}^T \\ \hline \begin{array}{c|c} \begin{matrix}1\\ \vdots \\ 1\end{matrix} & -\mathbf{I}_{(k-2)\times(k-2)} \end{array} & \begin{array}{c|c} \mathbf{I}_{(k-2)\times(k-2)} & \mathbf{0}_{(k-2)\times\frac{(k-2)(k-3)}{2}} \end{array} \end{array}\right] \qquad \frac{(k-1)(k-2)}{2} \times \frac{k(k-1)}{2}$$

Theorem: $null(\mathbf{A}_K) = span(\mathbf{S}_K)$.

Therefore, if $\mathbf{r} = \mathbf{A}_K \mathbf{x}$, then $\mathbf{x} = \mathbf{A}_K^+ \mathbf{r} + \mathbf{S}_K \mathbf{a}$ where $\mathbf{A}_K^+ = \mathbf{A}_K^T \left(\mathbf{A}_K \mathbf{A}_K^T\right)^{-1}$

Space-Time Power Scheduling for DPC-Multihop

General forms:

$$\min_{g_1(r_1, r_2, \cdots, r_{K-1}) \le 0} f_1\left(P_1, P_2, \cdots, P_{K-1}\right)$$

$$\max_{f_2\left(P_{1,} P_2, \cdots, P_{K-1}\right) \le 0} g_2(r_1, r_2, \cdots, r_{K-1})$$

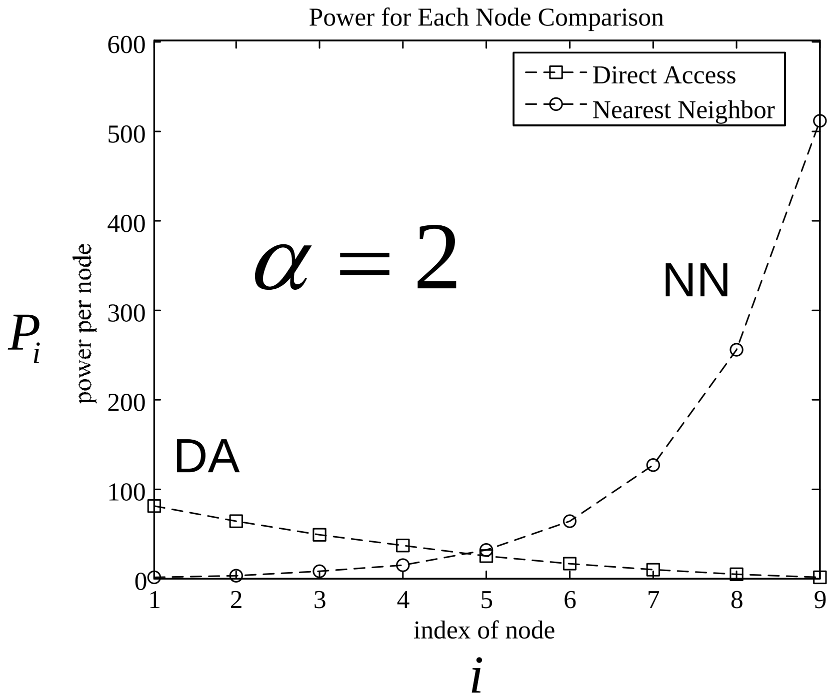
A specific example – minimization of L-norm of power:

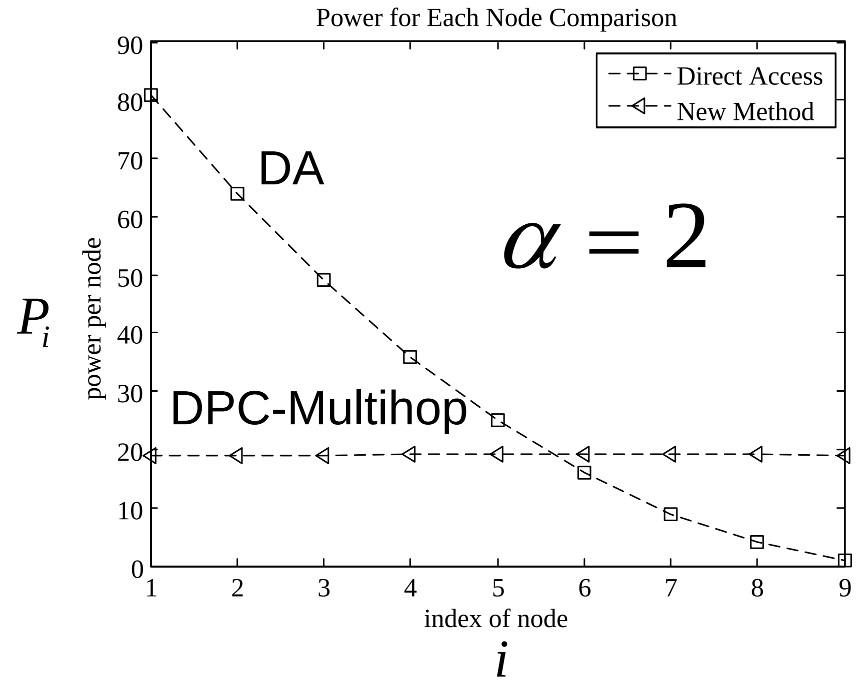
$$\min_{\mathbf{r} \le \mathbf{A}_K \mathbf{x}, \mathbf{x} \ge \mathbf{0}} \left(\sum_{i=1}^{K-1} P_i^L \right)^{1/L}$$

$$\Leftrightarrow \min_{\mathbf{r} = \mathbf{A}_K \mathbf{x}, \mathbf{x} \ge \mathbf{0}} \left(\sum_{i=1}^{K-1} P_i^L \right)^{1/L} \Leftrightarrow \min_{\mathbf{A}_K^{+} \mathbf{r} + \mathbf{S}_K \mathbf{a} \ge \mathbf{0}} \left(\sum_{i=1}^{K-1} P_i^L \right)^{1/L}$$

Illustration of the Performance of the DPC-Multihop Scheme

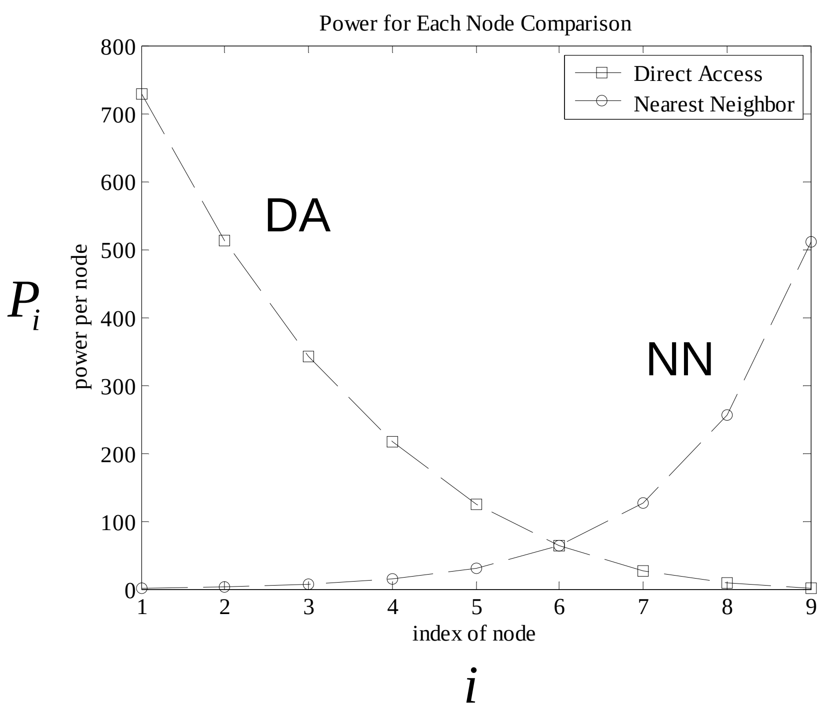
$$\min\left(\sum_{i=1}^{K-1} P_i^L\right)^{1/L}$$ where L=50 $$|h_{i,j}|^2 = \frac{1}{|i-j|^\alpha} \quad \sigma^2 = 1 \quad r_i = 1 \quad K = 10$$

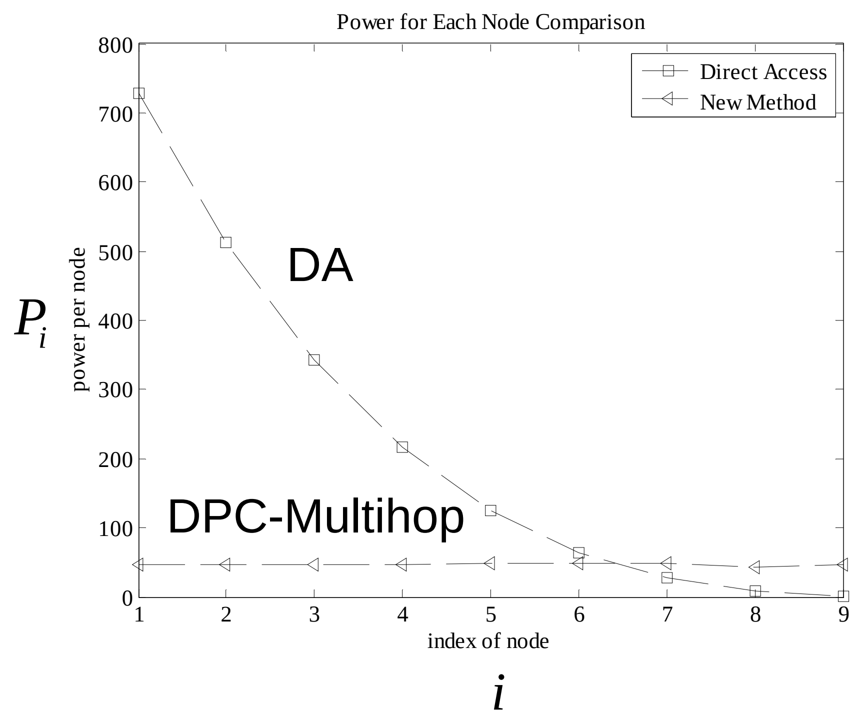




$$\alpha = 3$$

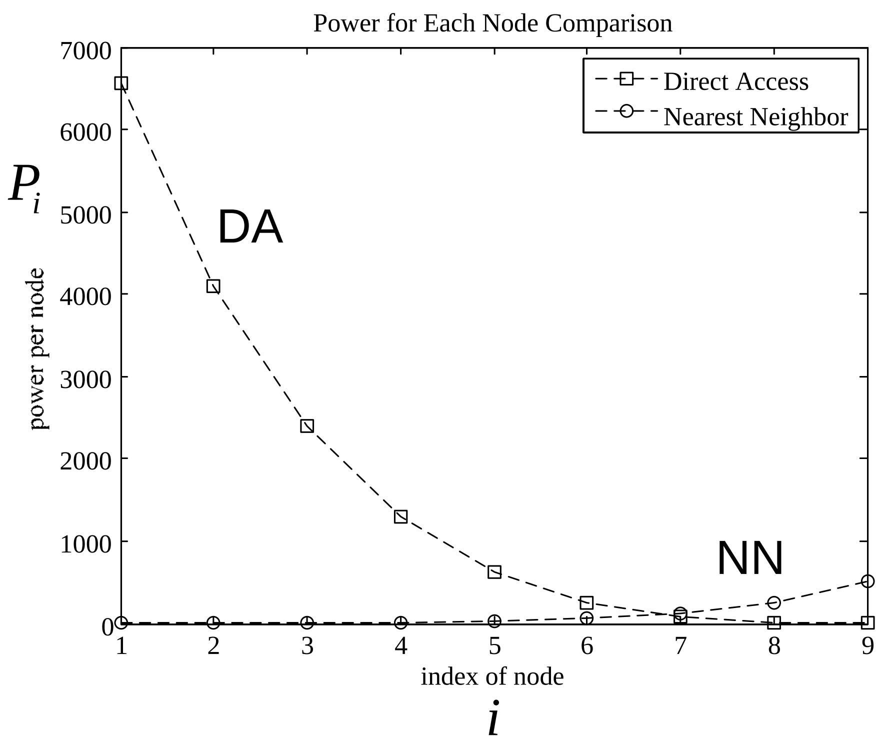
$$\min\left(\sum_{i=1}^{K-1} P_i^{L}\right)^{1/L}$$ where L=50 $$|h_{i,j}|^2 = \frac{1}{|i-j|^{\alpha}} \quad \sigma^2 = 1 \quad r_i = 1 \quad K = 10$$

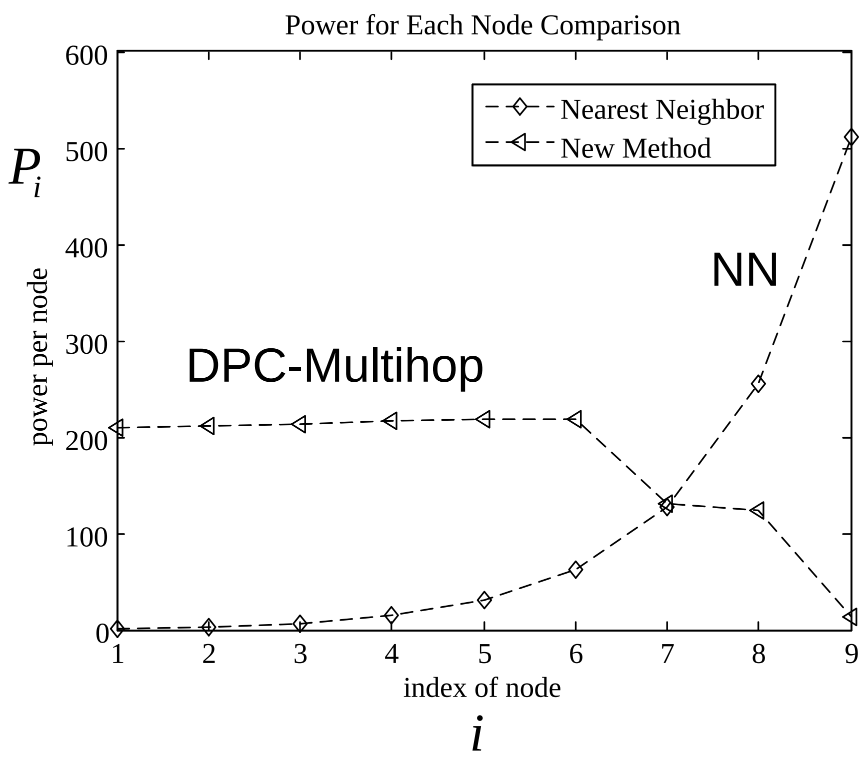




$\alpha = 4$

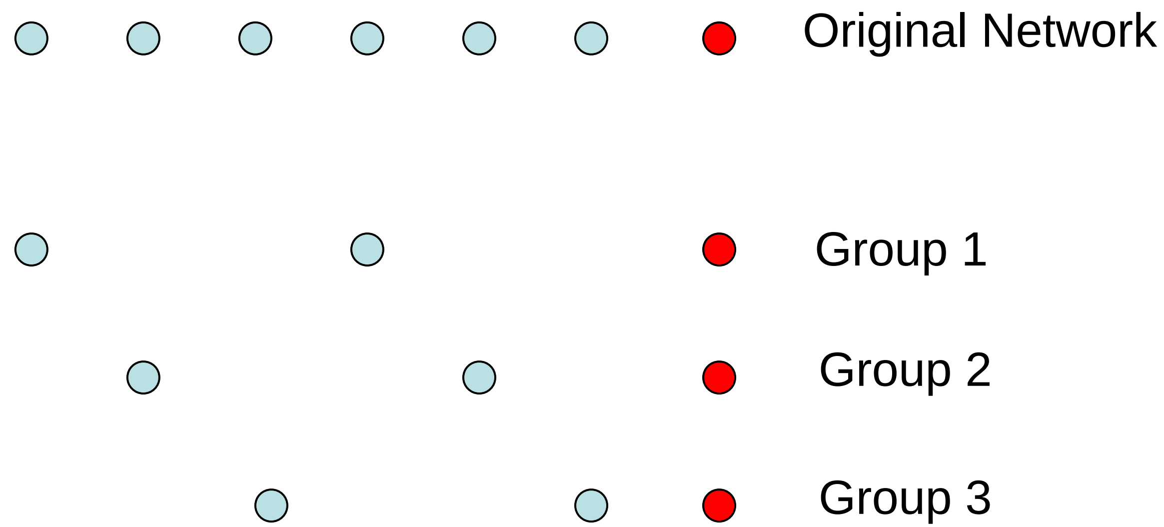
$$\min\left(\sum_{i=1}^{K-1} P_i^{\,L}\right)^{1/L} \quad \text{where L=50} \quad |h_{i,j}|^2 = \frac{1}{|i-j|^{\alpha}} \quad \sigma^2 = 1 \quad r_i = 1 \quad K = 10$$





Grouping for DPC-Multihop Space-Time Power Scheduling

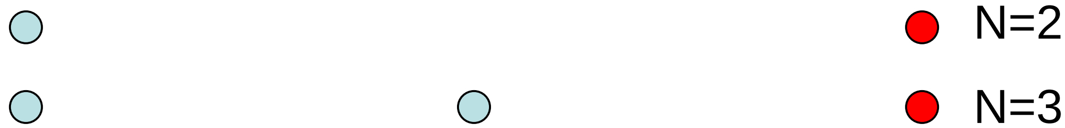
EXAMPLE



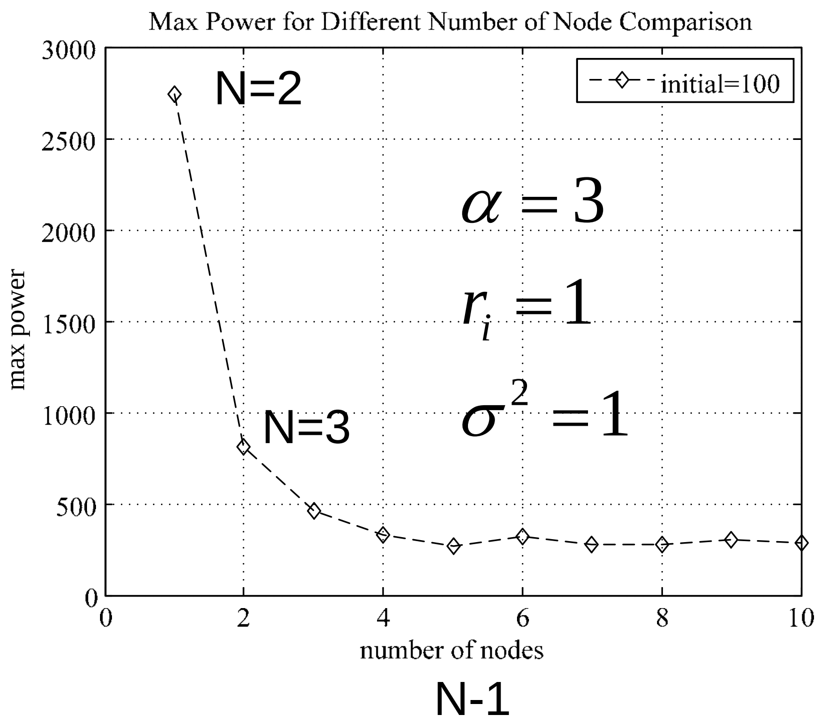
1. We can apply the DPC-Multihop scheme <u>to each group separately</u> to save the computation without much loss of performance. It also reduces the complexity of DPC.
2. How should we choose the size N of each group? Note that choosing size N=2 for each group is equivalent to the DA scheme.

Impact of Group Size N on the Performance of DPC-Multiple

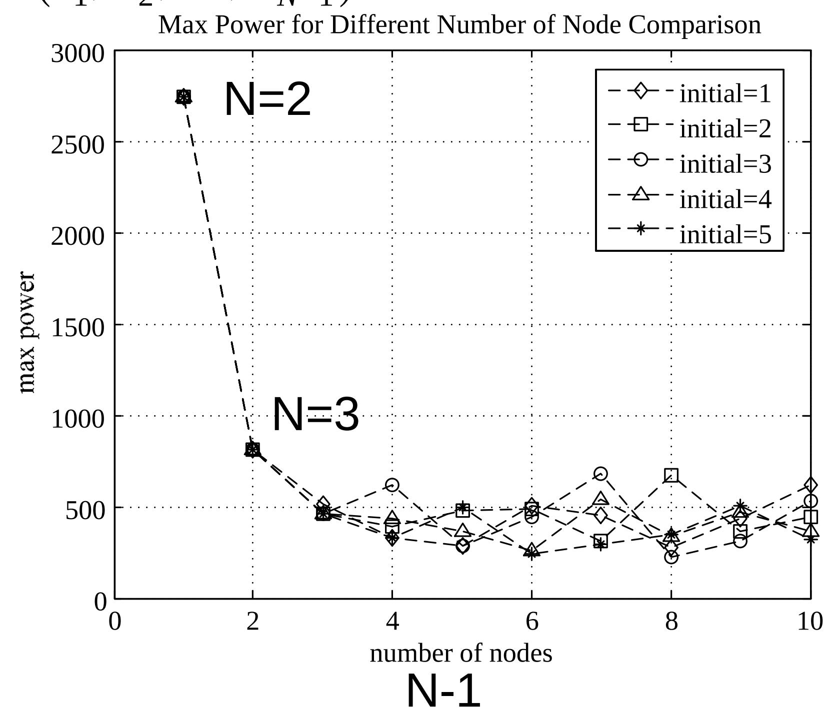
We locate N nodes linearly and uniformly over total distance D=14



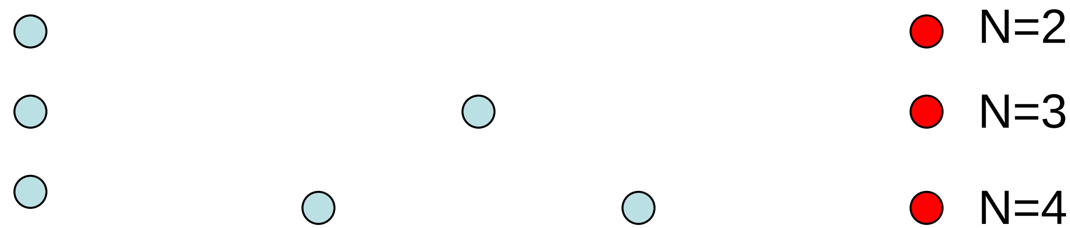
$$\max\left(P_1, P_2, \cdots, P_{N-1}\right)$$



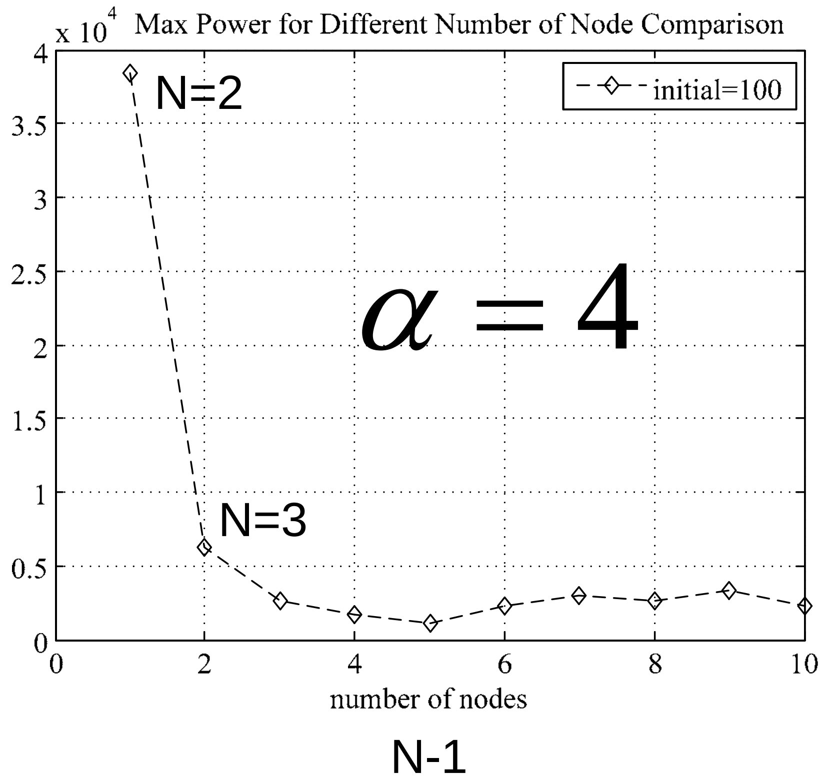
$$\max\left(P_1, P_2, \cdots, P_{N-1}\right)$$



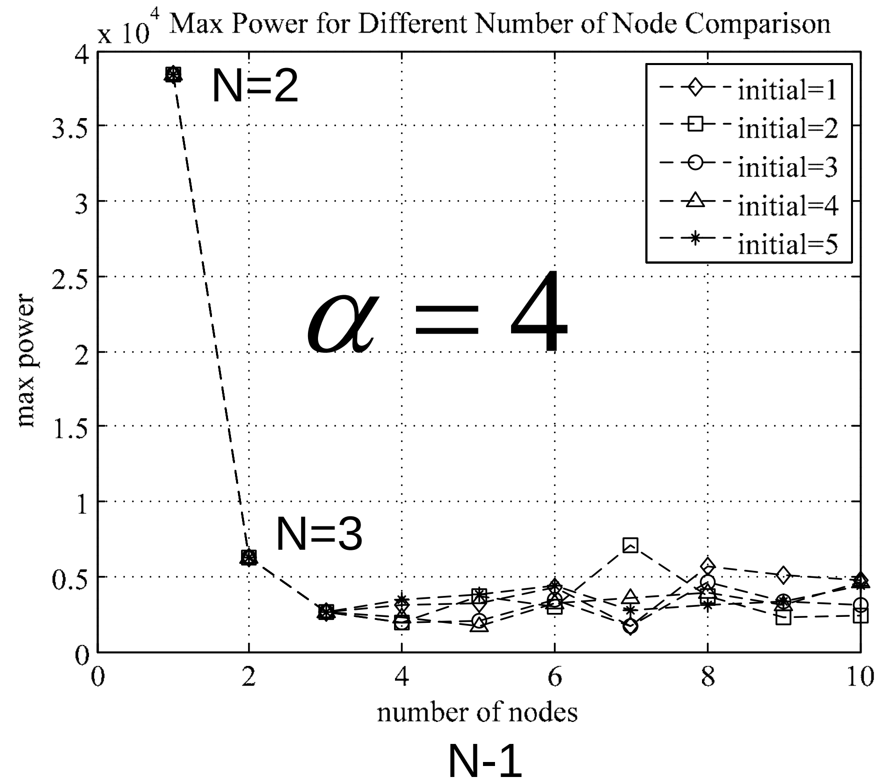
We locate N nodes linearly and uniformly over total distance D=14



$$\max\left(P_1, P_2, \cdots, P_{N-1}\right)$$

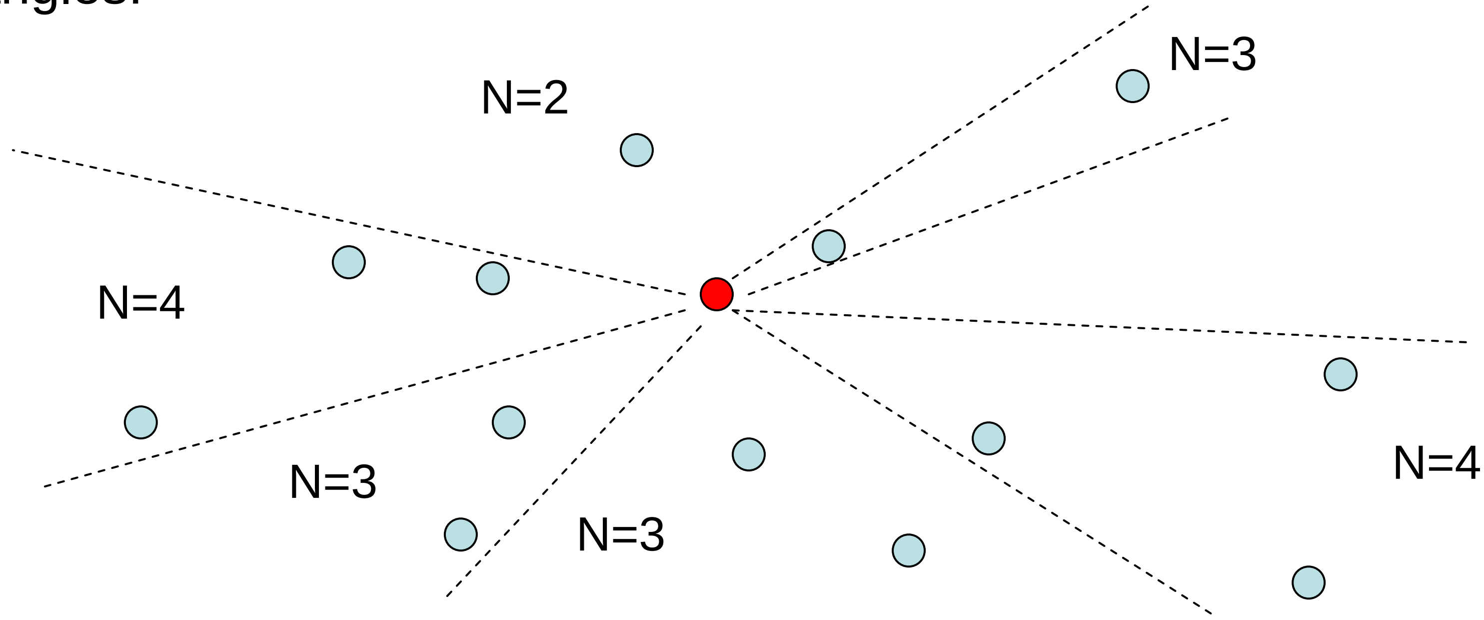


$$\max\left(P_1, P_2, \cdots, P_{N-1}\right)$$



Important Observations

1. Group size N=3 seems to provide the best performance-complexity tradeoff.
2. For N=3, the problem of minimizing the L-norm of power subject to the rate constraint is a convex problem, and the space-time power scheduling is very simple to compute.
3. For a random 2-D network of many nodes, we can do grouping by angles:



Conclusions

- The DPC-Multihop scheme provides a substantial capacity increase for wireless internet traffic.
- This scheme is feasible for stationary relay nodes for which channel state information (CSI) is available.
- The impact of CSI errors on this scheme is important and needs further investigation.