Back-Pressure Style Multicast in Wireless Networks with Random Linear Network Coding

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- Why *Random Linear Network Coding*?

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What is *Multicast*?

Multicast is to deliver data from one source S to a set of destinations $\mathbf{T}$: a *one-to-many* problem.

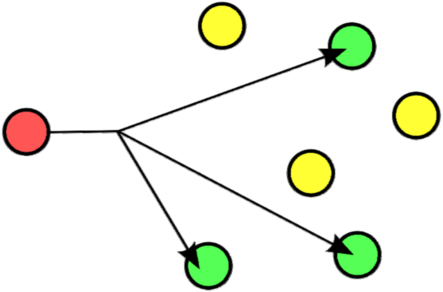

Figure: Multicast.

Why *Multicast*?

General case for *Unicast* and *Broadcast*.

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Unicast: one-to-one problem with $|\mathbf{T}| = 1$.

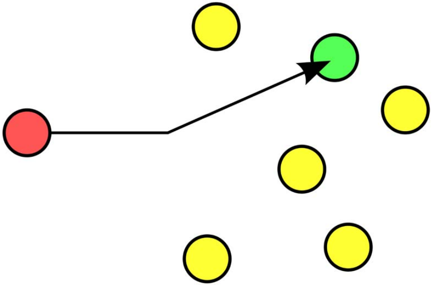

Figure: Unicast.

Why *Multicast*?

General case for *Unicast* and *Broadcast*.

Broadcast: one-to-all problem with $\mathbf{T} = \mathbf{V}$ ($\mathbf{V}$ is the node set of network).

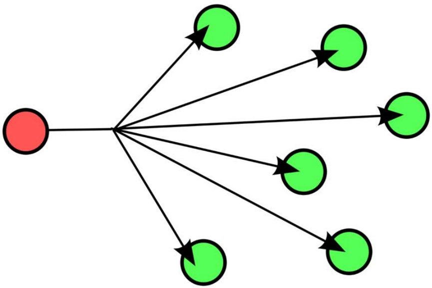

Figure: Broadcast.

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  Need an interference-free link scheduling.
- How to make use of the broadcasting nature of wireless transmission: one transmission can be received by multiple receivers concurrently.

Wireless transmission is modeled as a *hyperarc* instead of *directed edge*:

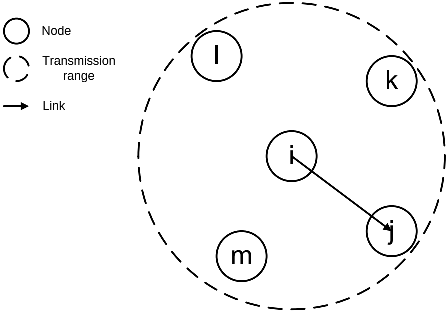

Figure: Directed edge $i \rightarrow j$.

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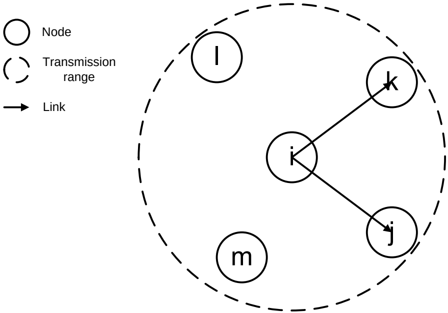

Figure: Hyperarc $i \to \{j, k\}$.

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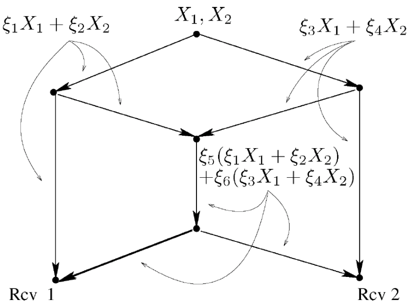

Figure: An example of random linear network coding.

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- Distributed compression: compress linearly correlated sources.
- Achieves multicast capacity with probability *exponentially* approaching 1 with the *length of code*.

Import result: The error probability decreases exponentially with the code length μ. Or equivalently, the probability for a successful decoding at the receiver should be $(1 - d/q)^{\eta}$, with d as the number of receivers, $q = 2^{\mu}$ as the finite space, and η is the maximum number of links receiving signals with independent randomized coefficients in any set of links constituting a flow solution from all sources to any receiver.

Important literature on random linear network coding:

- P.A. Chou, Y. Wu and K. Jain. *Practical Network Coding*. In Proc. of Allerton'03, Oct. 2003.
- R. Koetter and M. Médard. *An Algebraic Approach to Network Coding*. IEEE/ACM Transactions on Networking, vol. 11, no. 5, pp. 782-795, Oct. 2003.
- T. Ho,R. Koetter, M. Médard, D.R. Karger and M. Effros. *The Benefits of Coding over Routing in a Randomized Setting*. In Proc. of ISIT'03, Jun./Jul. 2003.
- T. Ho, M. Médard, R. Koetter, D.R. Karger, M. Effros, J. Shi and B. Leong. *A Random Linear Network Coding Approach to Multicast*, IEEE Transactions on Information Theory, vol. 52, no. 10, Oct. 2006.

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Traditional multicast algorithms:

- Tree-based algorithms.
-

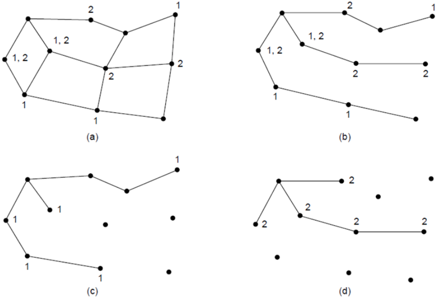

Figure: Tree-based multicast.

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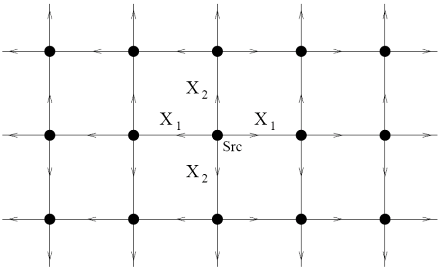

Figure: Mesh-based multicast.

Traditional multicast algorithms:

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Fixed routing table:

- Only suitable to static networks.
- Not adaptive to network dynamics.

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Back-Pressure style algorithms:

- Adaptive to network dynamics.
- Achievable full capacity region.
- Guaranteed throughput optimality.

Primal-Dual decomposition coupled with subgradient method.

- T. Ho and H. Viswanathan. *Dynamic Algorithms for Multicast with Intra-session Network Coding*. In Proc. of Allerton'05, Sept. 2005.
- L. Chen, T. Ho, S.H. Low, M. Chiang and J.C. Doyle. *Optimization Based Rate Control for Multicast with Network Coding*. In Proc. of INFOCOM'07, Aug. 2007.
- K. Rajawat, N. Gatsis and G.B. Giannakis. *Cross-Layer Designs in Coded Wireless Fading Networks with Multicast*. To appear in IEEE/ACM Transactions on Networking.

The only one with Lyapunov optimization.

- X. Yan. M.J. Neely and Z. Zhang. *Multicasting in Time-varying Wireless Networks: Cross-layer Dynamic Resource Allocation*. In Proc. of ISIT'07, Jun. 2007.

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Wired or wireless network?! Are you kidding me?!

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- $U_i^{cdk}(t)$: Queue of uncoded (c, k) packets for destination d at node i (network layer).

Capacity region Λ_K: set of all average admissible data rates r_i^{ck} with flow variables $\{f_{abZ}^{cdk}\}$ satisfying,

$$r_i^{ck} = \sum_{b,Z} f_{ibZ}^{cdk} - \sum_{a,Z} f_{aiZ}^{cdk}, \ \forall i, c, d, k$$

$$\sum_i r_i^{ck} = \sum_{a,Z} f_{adZ}^{cdk}, \ \forall c, d, k$$

$$\sum_{c,b,k} f_{abZ}^{cdk} \leq R_{aZ}, \ \forall a, Z, d$$

$$f_{abZ}^{cdk} \geq 0, \ \forall a, Z, b, c, d, k.$$

Utility Maximization Problem:

$$\begin{aligned}
\max \quad & \sum_{i,c} g_i^c(\mathbf{1}_K \gamma_i^c) \\
s.t. \quad & (\bar{P}_i) \leq (P_i^{av}) \\
& (P_{iZ}(t)) \leq (P_{iZ}^{peak}) \\
& \bar{\mathbf{r}} \geq \gamma \\
& 0 \leq \bar{\mathbf{r}} \leq \bar{\lambda} \\
& \bar{\mathbf{r}} \in \Lambda_K .
\end{aligned}$$

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- P_{iZ}^{peak}: peak power limit on hyperarc (i, Z).

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$$\bar{\lambda}_i^{ck} = \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{A_i^{ck}(\tau)\}.$$

Queue Dynamics

Backlog queues: for all $i,\ c,\ d,\ k$,

$$U_i^{cdk}(t+1) \leq \max\{U_i^{cdk}(t) - \sum_{b,Z} \mu_{ibZ}^{cdk}(t), 0\} + \sum_{a,Z} \mu_{aiZ}^{cdk}(t) + R_i^{ck}(t),$$

where

$$\sum_{c,k,b,Z} \mu_{ibZ}^{cdk}(t) \leq \mu_{max}^{out},\ \forall i, d,$$

$$\sum_{c,k,a,Z} \mu_{aiZ}^{cdk}(t) \leq \mu_{max}^{in},\ \forall i, d,$$

$$R_i^{ck}(t) \leq \hat{R}_i^c,\ \forall i, c, k.$$

Queue Dynamics

Virtual power queues: for all i,

$$X_i(t+1) = \max\{X_i(t) - P_i^{av}, 0\} + \sum_{Z} P_{iZ}(t),$$

where,

$$P_{iZ}(t) \leq P_{iZ}^{peak}, \ \forall (i, Z).$$

Queue Dynamics

Virtual flow state queues: for all i, c, k,

$$Y_i^{ck}(t+1) = \max\{Y_i^{ck}(t) - R_i^{ck}(t), 0\} + \gamma_i^{ck}(t),$$

where,

$$\gamma_i^{ck}(t) \leq \hat{R}_i^c, \ \forall i, c, k.$$

Let $\Theta(t) \triangleq [U(t), X(t), Y(t)]$, define Lyapunov function:

$$L(\Theta) \triangleq \frac{1}{2}[\sum_{i,c,d,k}(U_i^{cdk}(t))^2 + \sum_i X_i^2 + \sum_{i,c}(Y_i^{ck}(t))^2],$$

and Lyapunov drift

$$\Delta(\Theta(t)) \triangleq \mathbb{E}\{L(\Theta(t+1)) - L(\Theta(t))|\Theta(t)\}.$$

Apply *Drift-plus-penalty* method.

Flow control:

$$\begin{aligned} \max \quad & \sum_{i,c}(Y_i^{ck}(t) - \sum_{dk} U_i^{cdk}(t))R_i^{ck}(t) \\ s.t. \quad & 0 \leq R_i^{ck} \leq \min\{A_i^{ck}(t) + L_i^{ck}(t), \hat{R}_i^c\}. \end{aligned}$$

$$\begin{aligned} \max \quad & V g_i^c(\gamma_i^{ck}(t)) - Y_i^{ck}(t)\gamma_i^{ck}(t) \\ s.t. \quad & o \leq \gamma_i^{ck}(t) \leq \hat{R}_i^c. \end{aligned}$$

Routing and resource allocation:

$$\begin{aligned} \max \quad & \sum_{a,Z} \Big(\sum_{c,b,d,k} W_{ab}^{cdk}(t)\mu_{abZ}^{cdk}(t) - X_a(t)P_{aZ}(t) \Big) \\ s.t. \quad & P_{aZ}(t) \le P_{aZ}^{peak}, \ \forall a, Z, \end{aligned}$$

where

$$W_{ab}^{cdk}(t) = \max\{U_a^{cdk}(t) - U_b^{cdk}(t), 0\}, \ \forall a, b, c, d, k$$

$$\sum_{c,b,k} W_{ab}^{cdk}(t)\mu_{abZ}^{cdk}(t) \le R_{aZ}(t) \max_{c,k}\{\max_{b \in Z} W_{ab}^{cdk}(t)\}, \ \forall a, Z, d.$$

Here, $R_{aZ}(t) = \mu_{aZ}(\mathbf{S}(t), \mathbf{I}(t))$ and $\mathbf{I}(t) = \mathbf{P}(t)$.

Routing and resource allocation (Cont.): Select optimal session and block,

$$(c^*, k^*) = arg\max_{c,k}\{\sum_d \max\{W_{ab}^{cdk}(t), 0\}\},$$

and hyperarc weight,

$$W_{aZ}^* = \sum_d \max\{\max_{b \in Z}\{W_{ab}^{c^*dk^*}(t), 0\}\}.$$

Power assignment $\mathbf{P}_a^*(t) = (P_{aZ}^*(t))$ with,

$$\mathbf{P}_a^*(t) = arg\max_{P_{aZ} \leq P_{aZ}^{peak}} \sum_Z (\mu_{aZ}(\mathbf{S}(t), \mathbf{P}(t))W_{aZ}^* - X_a(t)P_{aZ}).$$

Network coding: for each hyperarc (a, Z):

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- For each node a: transmit random linear combination of packets from queues with $(c^*, d, k^*), d \in T_{aZ}^{c^* k^*}$ with power $P_{aZ}^*(t)$.
- For each $d \in T_{aZ}$: randomly select a receiver from set $\{b \in Z : b = arg\, \max_{b \in Z} W_{ab}^{c^* d k^*}\}$.

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- One queue for each receiver on each node; not scalable with respective to network size or receiver set size.
- Equivalent to multiple linearly correlated unicast sessions, among which intersession network coding is available; waste of network capacity and transmission power.
- Single rate multicast; overall throughput is limited by the receiver with minimum achievable data rate.