Internet Service in Developing Regions Through Network Coding*

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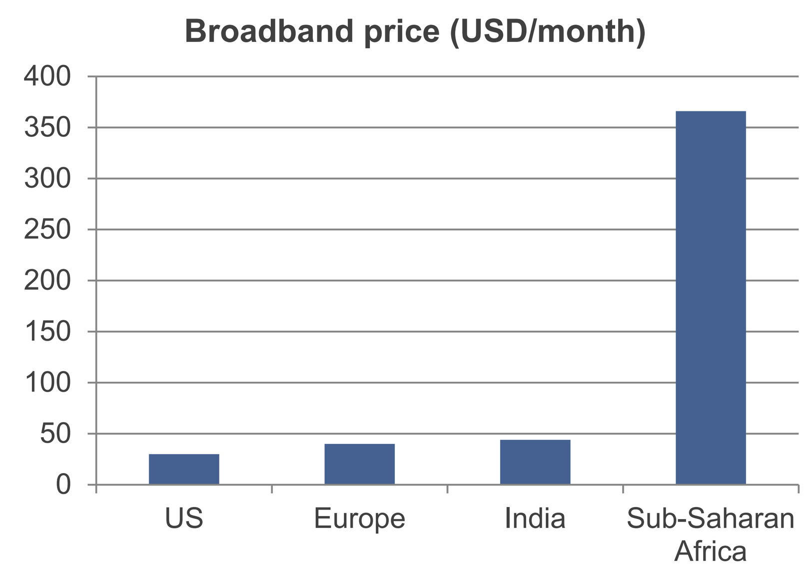
Problem Space

The *Digital Divide* manifests itself in networking as a low penetration of internet services in developing regions. Wherever data services are available, their price is order of magnitude higher than in the developed world.



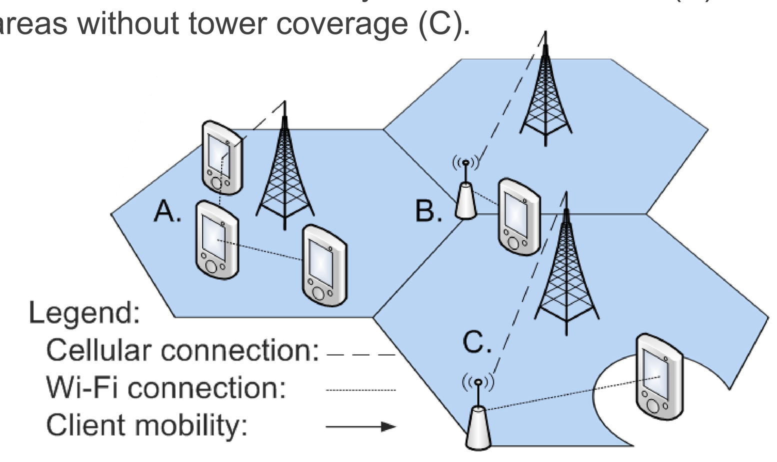
At the same time, cellular deployments in developing regions have been far more successful and widespread. However, by and large they do not offer data services and their high subscription price renders them unaffordable to much of the rural population.

There have also been a number of rural mesh deployments, where Internet connectivity available at a rural school or hospital is extended to the community through a Wi-Fi mesh network. While these are isolated deployments that serve small communities, nevertheless an important observation can be made in that most of the data traffic is local to the community and centered around access to locally cached websites or multimedia or medical record exchange.

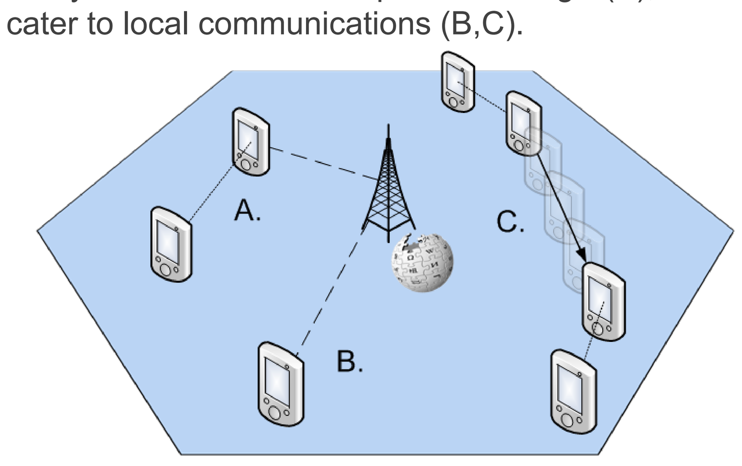
A technical problem worth investigating is how to provide **low cost data communications** that **leverage existing cellular deployments** and **cater to local patterns of communications**.

Network Setting

In *Multihop Cellular Network (MCNs)* cellular connectivity is augmented by client-to-client communications [Lin00]. MCNs can reduce cellular channel load, where clients with poor connectivity to the tower forward their data through better connected neighbors (A). MCNs can also extend cellular connectivity to overloaded cells (B), or to areas without tower coverage (C).



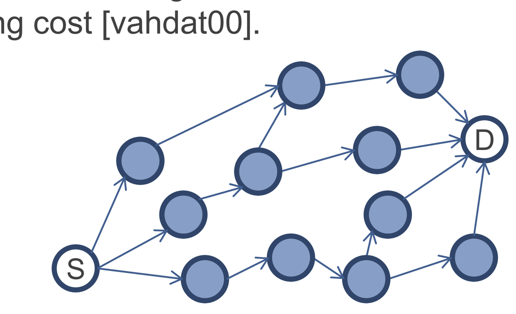
Rural cellular networks are characterized by lower client density and larger cells. Long range communications require more bandwidth to mask errors, and so cellular spectrum remains a scarce resource.
To cater to community traffic patterns, rural MCNs need not only to reduce cellular spectrum usage (A), but also to cater to local communications (B,C).



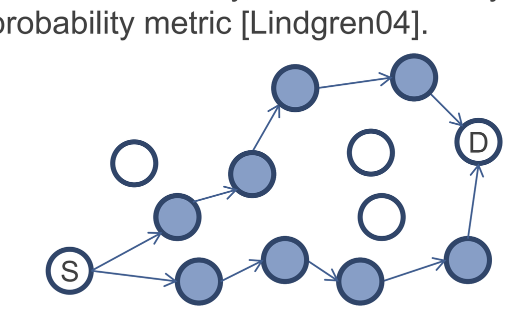
Because cellular spectrum or contemporaneous routing paths may not be available, **rural MCNs need to support opportunistic forwarding**.

Existing Solutions

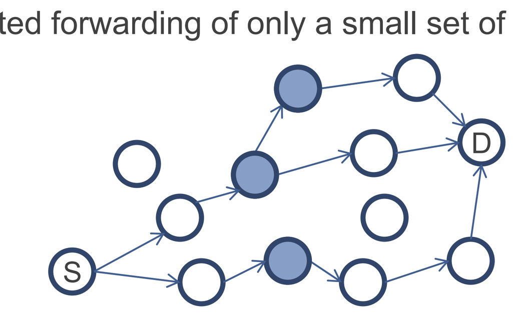
Opportunistic forwarding has been the focus of research in Delay Tolerant Networks (DTNs). Most simply, end-to-end deliveries in a DTN can be achieved by flooding a *bundle* of data during all node contacts, albeit at a high forwarding cost [vahdat00].



To reduce the cost of flooding a number of flood scoping techniques have been proposed. Most notably PRoPHET forwards bundle copies only to nodes better suited to effect a delivery, as estimated by a transitive delivery probability metric [Lindgren04].



But, the high cost of flooding creates network congestion, and so, we previously proposed Cloud Routing (CR) [Wittie09]. In CR, network and traffic state are disseminated over a control channel which allows the targeted forwarding of only a small set of bundles.



But, reliability through replication wastes network resources.

Intra-flow Network Coding

One of many networks coding (NC) techniques is to randomly encode data forwarded on each path, so that data arriving on multiple paths is innovative, with high probability. We make use of technique by Chou, where codes are embedded in packets themselves [Chou03].

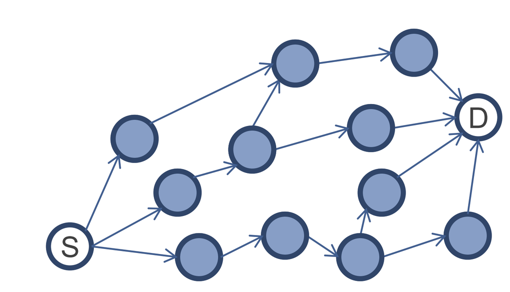
We partition n bytes of data into a $D_{p\times n/p}$ data matrix. We also allocate an $E_{p\times p}$ encoding matrix, initially I. To encode a *code piece*, we generate a random *encoding vector* $\boldsymbol{v}_{1\times p}, \boldsymbol{v}_i \in \mathcal{GF}(8)$.
A coded piece is the concatenation:

$$[\ \boldsymbol{v}E \mid \boldsymbol{v}D\ ]_{1\times(p+n/p)}$$

As the coded pieces accumulate at the destination, they form a matrix, which can be inverted by Gaussian elimination to decode the original data.

$$\begin{bmatrix} \boldsymbol{v}_1E_1 \mid \boldsymbol{v}_1D_1 \\ \boldsymbol{v}_2E_2 \mid \boldsymbol{v}_1D_1 \\ \vdots \mid \vdots \\ \boldsymbol{v}_3E_3 \mid \boldsymbol{v}_1D_1 \end{bmatrix} \xrightarrow{Gaussian\ \ elim.} \begin{bmatrix} I & \mid & D \end{bmatrix}_{p\times(p+n/p)}$$

Network Coding Probabilistic Routing (NCPR) takes advantage of NC to forward only a fraction (d) of a bundle during each node contact [Widmer05].

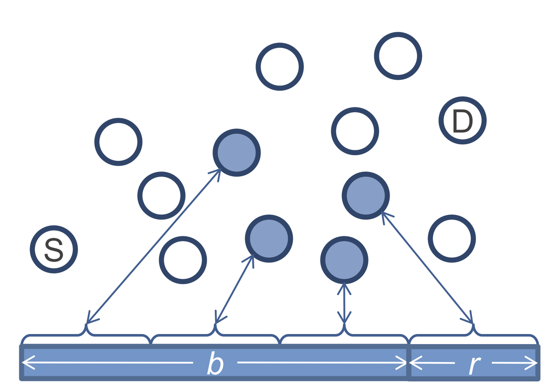


But, there is tradeoff between high delivery rates and high forwarding load, and a more dynamic mechanism for reliability is needed.

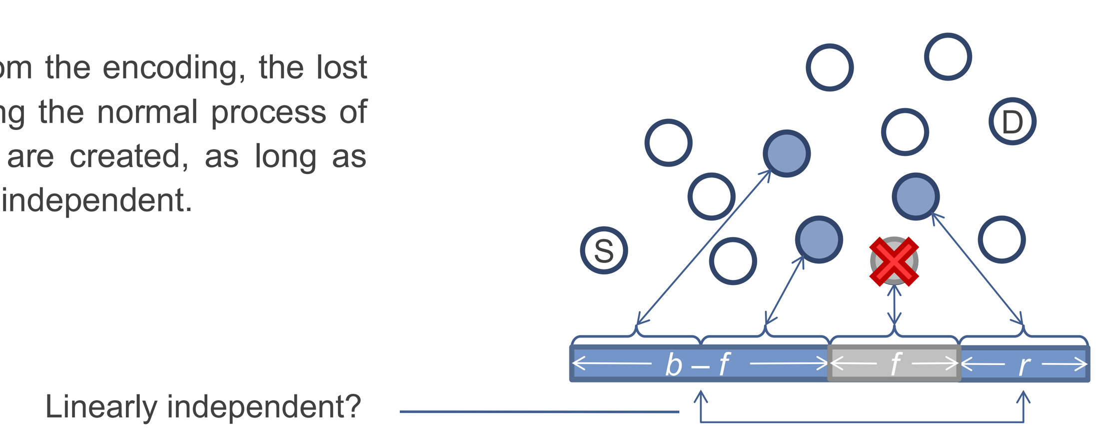
Semi-Innovative Set Routing (SISR)

SISR (scissor) maintains a small amount of in-flight data (similarly to CR) and spreads that data over multiple paths using network coding (similarly to NCPR).

- Coded pieces required to decode bundle: $b = p$
- Redundant coded pieces: $r = \frac{b}{4}$
- Maximum coded pieces at node (bundle fraction): $f = r$

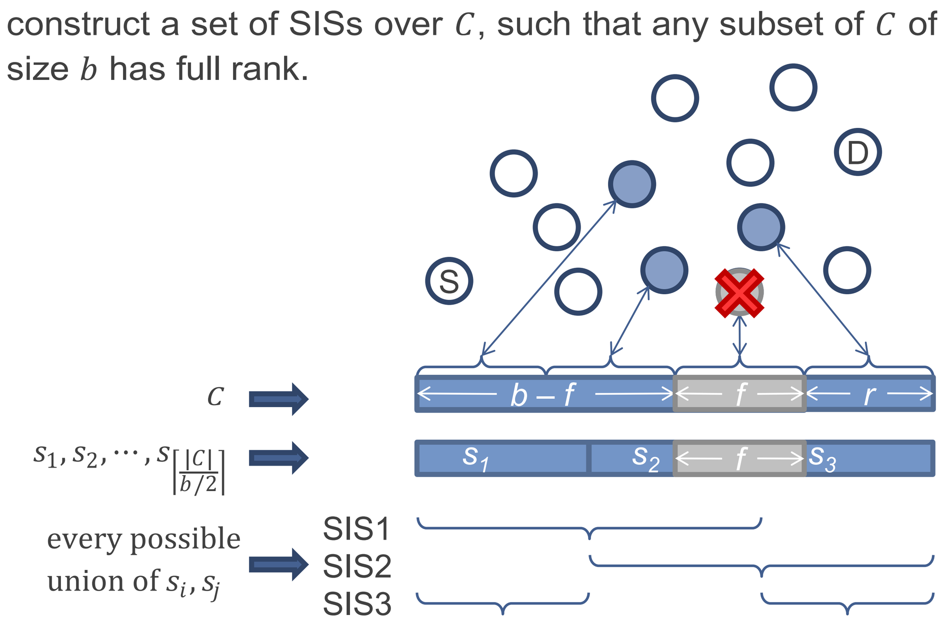


When any bundle fraction f is lost from the encoding, the lost redundancy can be regenerated during the normal process of forwarding, when new coded pieces are created, as long as remaining b coded pieces are linearly independent.

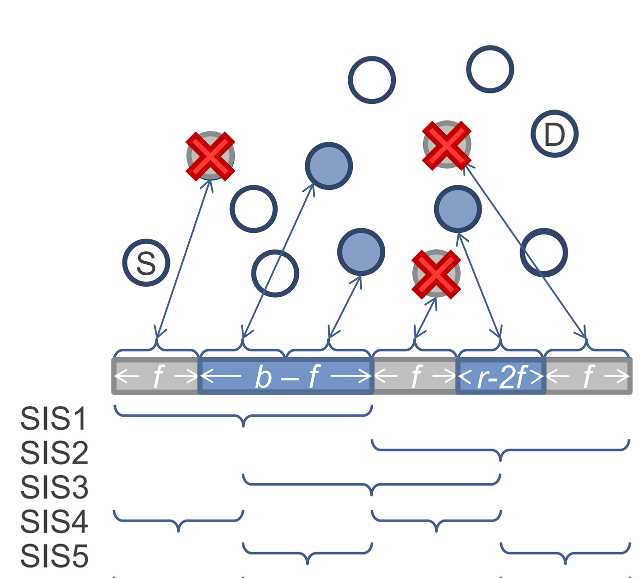


Let a ***semi-innovative set (SIS)*** s be a set of linearly independent coded pieces.

Given a set of coded pieces $C, |C| = b + r, r \geq 1$, we can construct a set of SISs over C, such that any subset of C of size b has full rank.



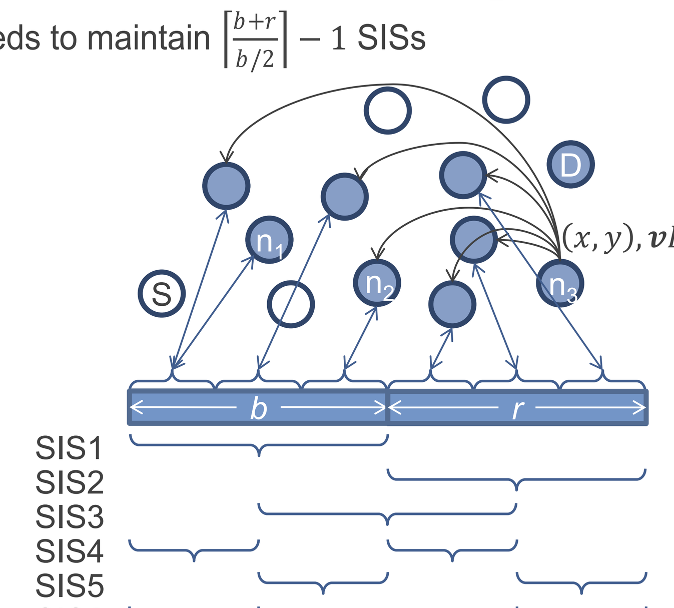
SISs can be constructed to tolerate any number of losses $l = \lceil r/f \rceil, f \leq r$.
For example, for $l = 3 \rightarrow C = 2b, f = \frac{1}{3}$:



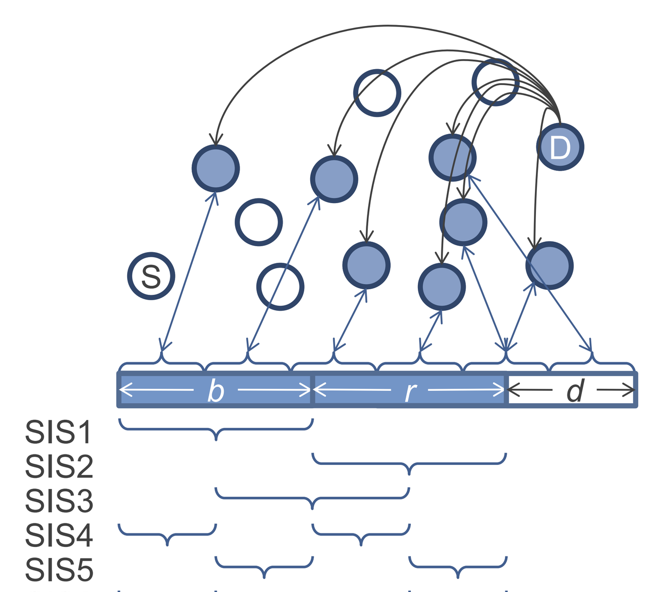
Embedded codes disseminated over the control channel to announce forwarding progress.

While the number of SISs grows exponentially as $\binom{\left[\frac{b+r}{b/2}\right]}{2}$,

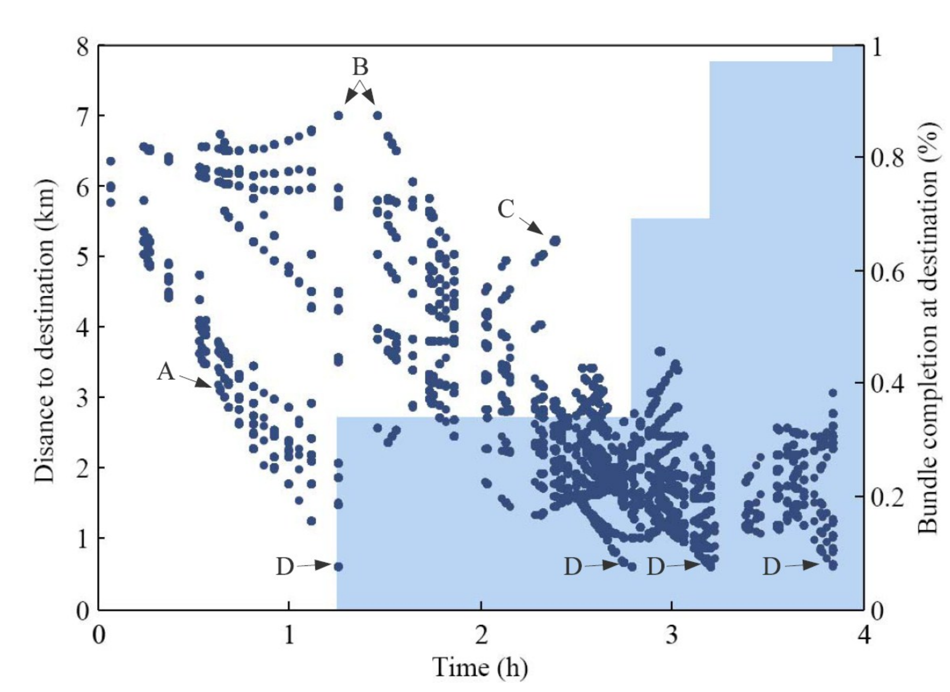
each node only needs to maintain $\left[\frac{b+r}{b/2}\right] - 1$ SISs



When d coded pieces are delivered, the global encoding adjusts accordingly.



An Illustrating Example

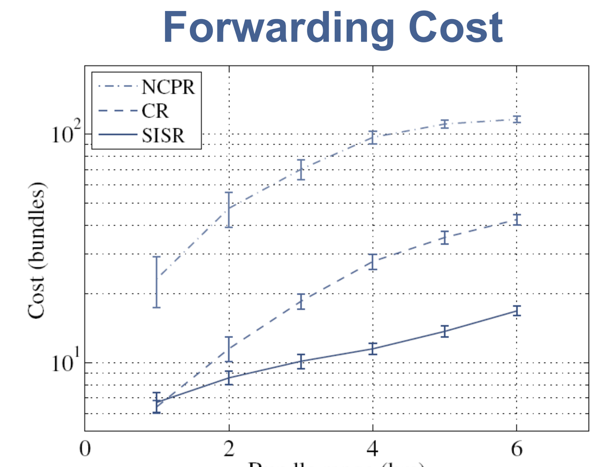


To further clarify the exposition of SISR, we present a brief example of a bundle's progress in Figure 4. The horizontal axis marks simulation time, the left vertical axis marks distance to destination of coded pieces carried by individual nodes, while the right vertical axis the amount of data decoded at the destination. Each of the points represents the position of some coded piece. As time passes, data is forwarded during opportunistic contacts and makes progress towards the destination, as in A. Nodes that no longer approach the destination either hand off their data to better forwarders, as in B, or delete their content, as in C, when they no longer contain data innovative for any SIS. As nodes come to within the communication distance of the destination, as in D, data received at the destination increases the amount of data that can be decoded. Finally, the destination decodes the entire bundle at time 3:50.

Evaluation

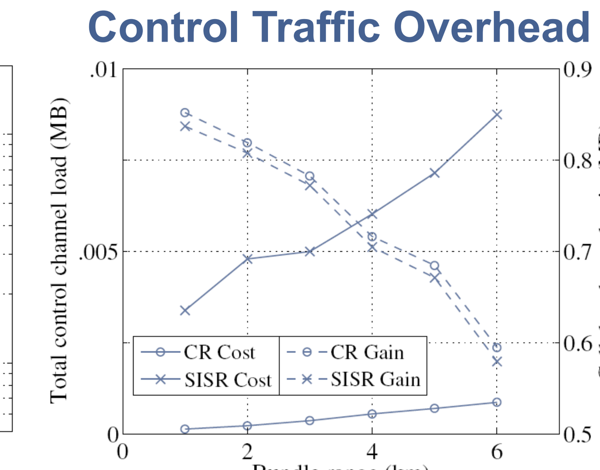
We want to compare the performance of SISR, the proposed solution, with CR, which forwards a small set of bundles, and with NCPR, which floods network coded data. We configure the simulated network to represent the area a typical rural community of around a hundred users might occupy: 100 nodes in a 8x8 km area. We set the mobility profile to walking speeds and communication range to 600m. We configure the forwarding protocols as follows: NCPR – d configured for 100% delivery at 6km, CR – lowest forwarding cost at delay comparable to larger traffic clouds, SISR – lowest delay at 6km. We simulate a single 1MB bundle between two random nodes.

Forwarding Cost



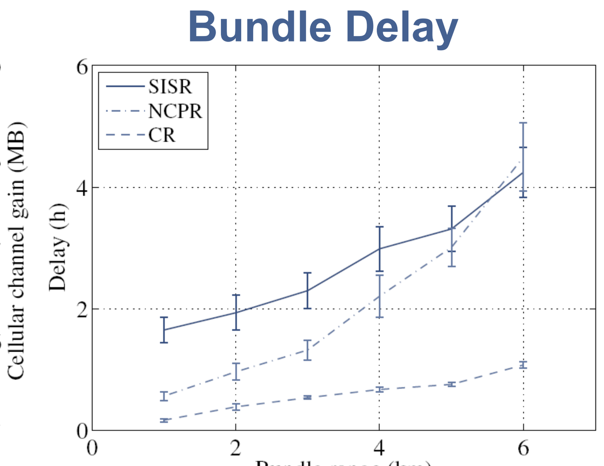
Forwarding cost is counted as the amount of data forwarded in the network before a bundle is delivered. NCPR has the highest forwarding cost due to flooding. CR has the next lowest cost, since it only forwards a small set of data copies. **SISR achieves the lowest forwarding cost** since it forwards a fraction of bundle's data on each path.

Control Traffic Overhead



Control channel load is comprised of node position updates and bundle progress notifications.
Cellular channel gain is the amount of delivered data minus control traffic. Most of the control traffic is due to node position updates, as bundle progress notifications are infrequent. In this view, **cellular channel gain will be higher when amortized over multiple flows.**

Bundle Delay



Bundle delay is the end-to-end forwarding delay of an entire bundle or enough coded pieces to decode it. SISR has the highest delay as delivery delay depends on the arrival of the last coded piece. In spite of flooding, NCPR also has high delay since it can use up the forwarding allowance before a delivery at long flow ranges. CR has the shortest delay of the first bundle copy.

Conclusions

In this work we have proposed SISR, a new routing mechanism for sparse MCNs. SISR leverages MCN infrastructure to exchange protocol control traffic to enable end-to-end management of network coding and opportunistic forwarding. Global network state knowledge allows SISR to forward only innovative data. SISR also maintains encoding redundancy that can tolerate losses on any number of nodes as long as the opportunistic forwarding rate exceeds the loss rate. These novel mechanisms allow SISR to reduce the cost of opportunistic routing by a factor of two over previous solutions. The integration of SISR in cellular deployments is expected to significantly reduce infrastructure load of data services. Reduced loads allow for more clients and a lower service price point, which can open currently unaffordable Internet services to more clients in developing regions.

* This work was originally presented at SECON 2009 in Rome, Italy.