15-744: Computer Networking

L-12 Wireless Broadcast

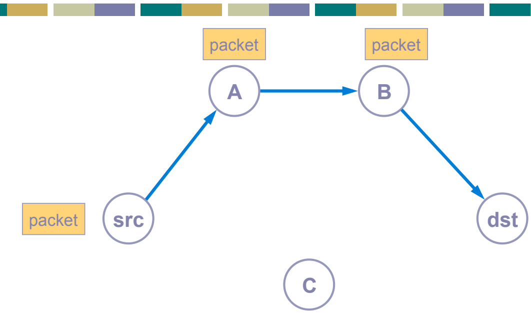
Taking Advantage of Broadcast

- Opportunistic forwarding
- Network coding
- Assigned reading
  - XORs In The Air: Practical Wireless Network Coding
  - ExOR: Opportunistic Multi-Hop Routing for Wireless Networks

Outline

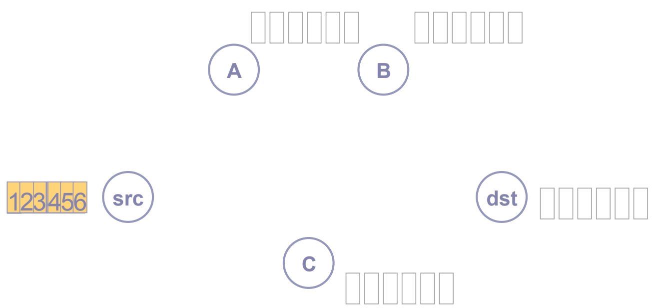
- Opportunistic forwarding (ExOR)
- Network coding (COPE)
- Combining the two (MORE)

Initial Approach: Traditional Routing



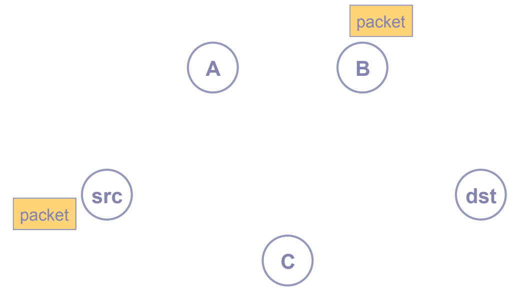
- Identify a route, forward over links
- Abstract radio to look like a wired link

Radios Aren't Wires



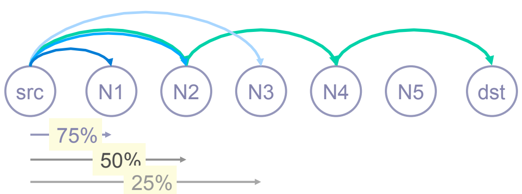
- Every packet is broadcast
- Reception is probabilistic

Exploiting Probabilistic Broadcast



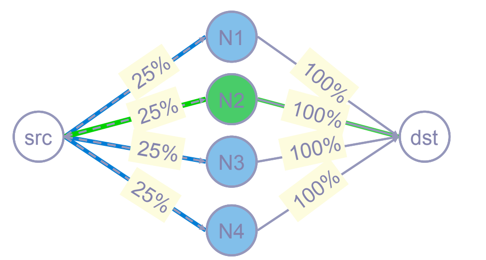
- Decide who forwards after reception
- Goal: only closest receiver should forward
- Challenge: agree efficiently and avoid duplicate transmissions

Why ExOR Might Increase Throughput



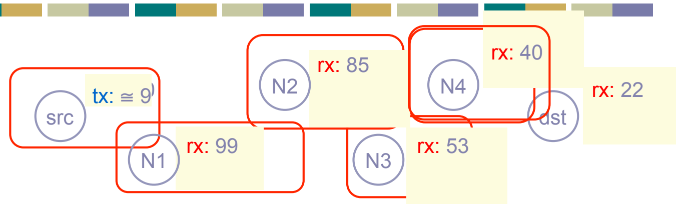
- Best traditional route over 50% hops: $3(^1/_{0.5}) = 6$ tx
- Throughput $\cong {}^1/_{\#\ \text{transmissions}}$
- ExOR exploits lucky long receptions: 4 transmissions
- Assumes probability falls off gradually with distance

Why ExOR Might Increase Throughput



- Traditional routing: $^1/_{0.25} + 1 = 5$ tx
- ExOR: $^1/_{(1-(1-0.25)^4)} + 1 = 2.5$ transmissions
- Assumes independent losses

ExOR Batching



- Challenge: finding the closest node to have rx'd
- Send batches of packets for efficiency
- Node closest to the dst sends first
  - Other nodes listen, send remaining packets in turn
- Repeat schedule until dst has whole batch

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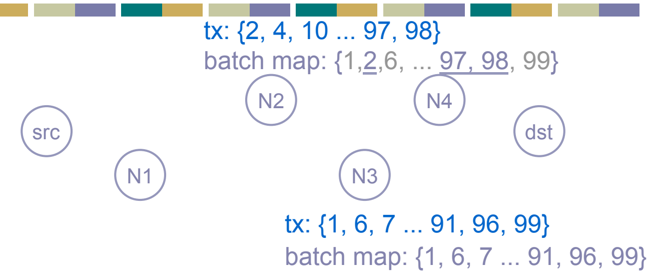
Reliable Summaries



- Repeat summaries in every data packet
- Cumulative: what all previous nodes rx'd
- This is a gossip mechanism for summaries

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Priority Ordering

- Goal: nodes "closest" to the destination send first
- Sort by ETX metric to dst
  - Nodes periodically flood ETX "link state" measurements
  - Path ETX is weighted shortest path (Dijkstra's algorithm)
- Source sorts, includes list in ExOR header

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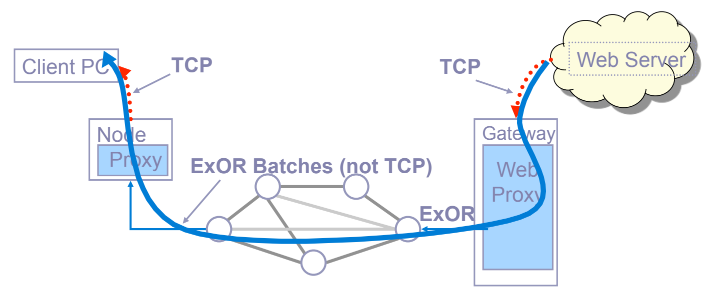
Using ExOR with TCP



- Batching requires more packets than typical TCP window

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Discussion

- Exploits radio properties, instead of hiding them
- Scalability?
- Parameters – 10%?
- Overheads?

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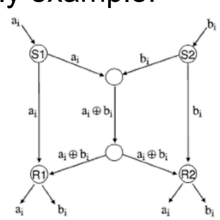
Background

- Famous butterfly example:



- All links can send one message per unit of time
  - Coding increases overall throughput

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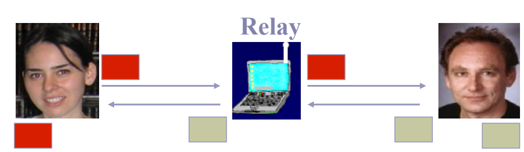
Background

- Bob and Alice



Require 4 transmissions

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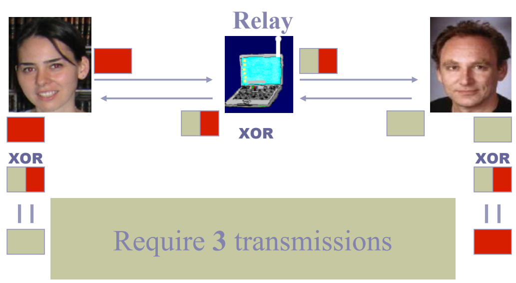
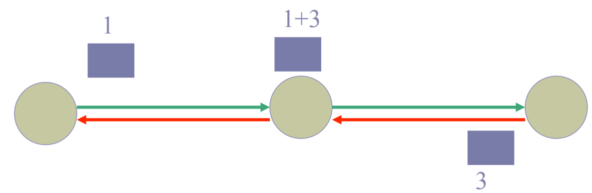
Background

- Bob and Alice



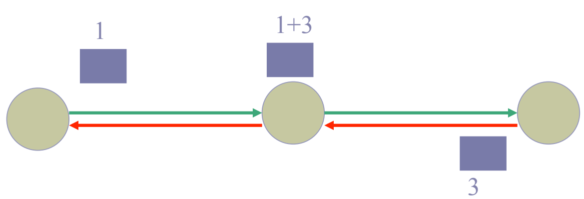
Coding Gain

- Coding gain = 4/3

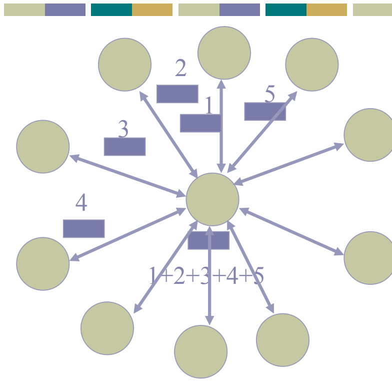


Throughput Improvement

- UDP throughput improvement ~ a factor 2 > 4/3 coding gain



Coding Gain: more examples

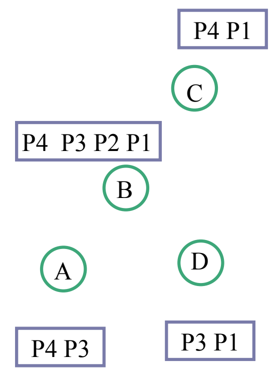


Without opportunistic listening, coding [+MAC] gain=2N/(1+N) → 2.
With opportunistic listening, coding gain + MAC gain → ∞

COPE (Coding Opportunistically)

- Overhear neighbors' transmissions
- Store these packets in a ***Packet Pool*** for a short time
- Report the packet pool info. to neighbors
- Determine what packets to code based on the info.
- Send encoded packets

Opportunistic Coding



B's queue	Next hop
P1	A
P2	C
P3	C
P4	D

Coding	Is it good?
P1+P2	Bad (only C can decode)
P1+P3	Better coding (Both A and C can decode)
P1+P3+P4	Best coding (A, C, D can decode)

Packet Coding Algorithm

- When to send?
  - Option 1: delay packets till enough packets to code with
  - Option 2: never delaying packets -- when there's a transmission opportunity, send packet right away
- Which packets to use for XOR?
  - Prefer XOR-ing packets of similar lengths
  - Never code together packets headed to the same next hop
  - Limit packet re-ordering
  - XORing a packet as long as all its nexthops can decode it with a high enough probability

Packet Decoding

- Where to decode?
  - Decode at each intermediate hop
- How to decode?
  - Upon receiving a packet encoded with n native packets
    - find n-1 native packets from its queue
    - XOR these n-1 native packets with the received packet to extract the new packet

Prevent Packet Reordering

- Packet reordering due to async acks degrade TCP performance
- Ordering agent
  - Deliver in-sequence packets immediately
  - Order the packets until the gap in seq. no is filled or timer expires

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Summary of Results

- Improve UDP throughput by a factor of 3-4
- Improve TCP by
  - wo/ hidden terminal: up to 38% improvement
  - w/ hidden terminal and high loss: little improvement
- Improvement is largest when uplink to downlink has similar traffic
- Interesting follow-on work using analog coding

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Reasons for Lower Improvement in TCP

- COPE introduces packet re-ordering
- Router queue is small ➔ smaller coding opportunity
  - TCP congestion window does not sufficiently open up due to wireless losses
- TCP doesn't provide fair allocation across different flows

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Discussion

- Wired vs. wireless coding
- Traffic patterns
- Scale

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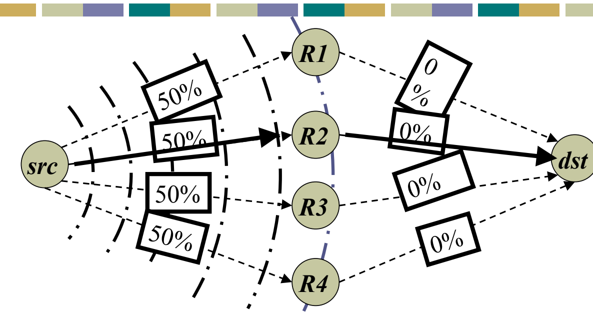
Use Opportunistic Routing



Opportunistic routing promises large increase in throughput

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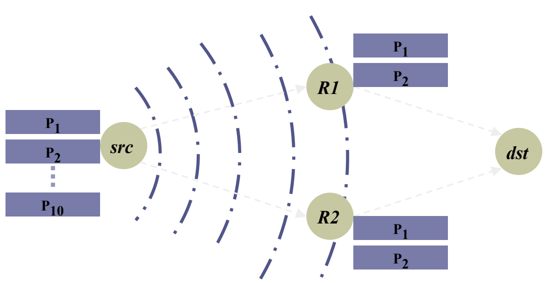
But

- Overlap in received packets → Routers forward duplicates



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ExOR

- State-of-the-art opp. routing, ExOR imposes a global scheduler:
- Requires full coordination; every node must know who received what
- Only one node transmits at a time, others listen

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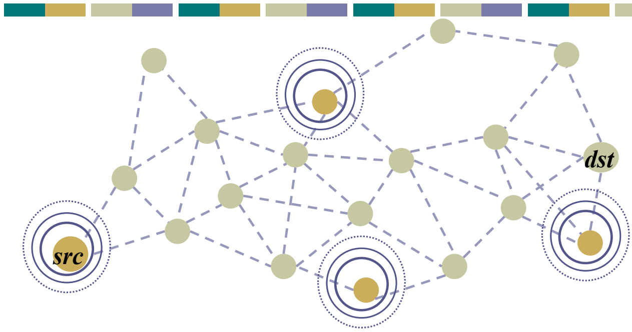
Global Scheduling



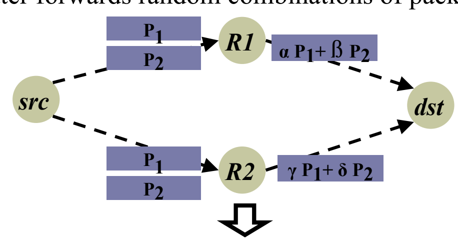
- Global coordination is too hard
- One transmitter → You lost spatial reuse!

MORE (Sigcomm07)

- Opportunistic routing with no global scheduler and no coordination
- Uses random network coding
- Experiments show that randomness outperforms both current routing and ExOR

Go Random

Each router forwards random combinations of packets

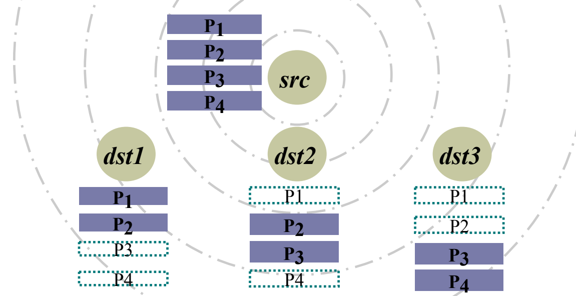


Randomness prevents duplicates

No scheduler; No coordination

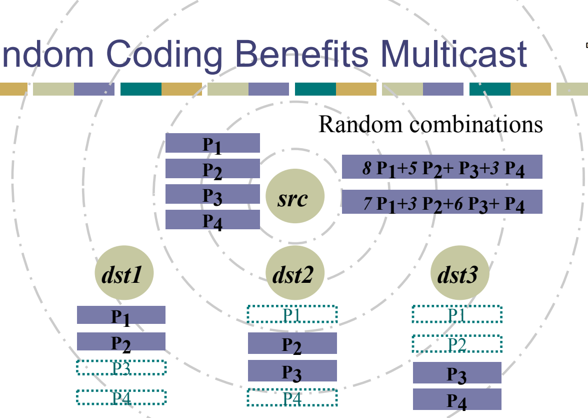
Simple and exploits spatial reuse

Random Coding Benefits Multicast



Without coding → source retransmits all 4 packets

Random Coding Benefits Multicast



Without coding → source retransmits all 4 packets

With random coding → 2 packets are sufficient

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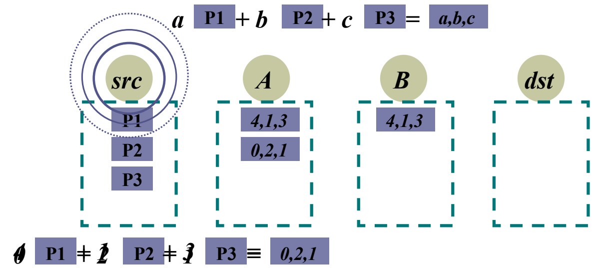
MORE

- Source sends packets in batches
- Forwarders keep all heard packets in a buffer
- Nodes transmit linear combinations of buffered packets



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MORE

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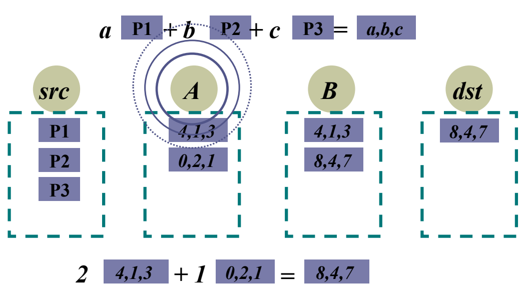

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MORE

- Source sends packets in batches
- Forwarders keep all heard packets in a buffer
- Nodes transmit linear combinations of buffered packets
- Destination decodes once it receives enough combinations
  - Say batch is 3 packets

1 P1 + *3* P2 + *2* P3 = *1,3,2*

5 P1 + *4* P2 + *5* P3 = *5,4,5*

4 P1 + *5* P2 + *5* P3 = *4,5,5*

- Destination acks batch, and source moves to next batch

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Summary/Midterm

- Wireless broadcast enables new protocol designs
- Key challenge is coordination
- Midterm
  - Closed book, coverage includes today
  - Similar in style to sample
  - Will post HW solutions/lecture video tonight
  - Office hours tomorrow
    - Srini: 10am-11am, Xi: 3pm-4pm

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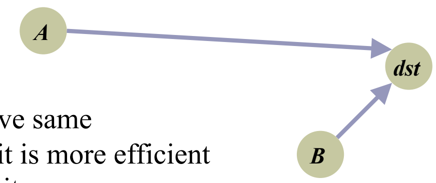
But How Do We Get the Most Throughput?

- Naïve approach transmits whenever 802.11 allows



If *A* and *B* have same information, it is more efficient for B to send it

Need a Method to Our Madness

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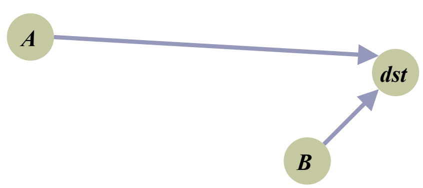
Probabilistic Forwarding



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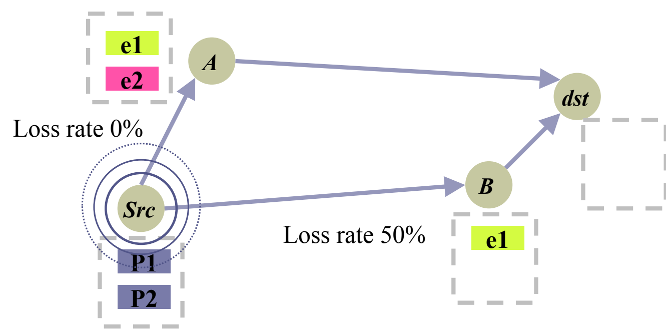
Probabilistic Forwarding



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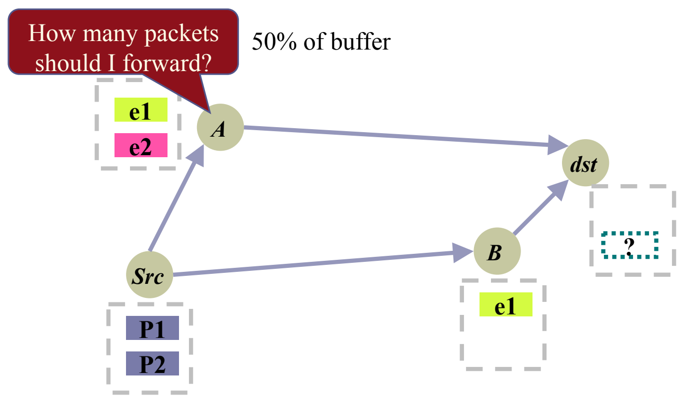
Probabilistic Forwarding



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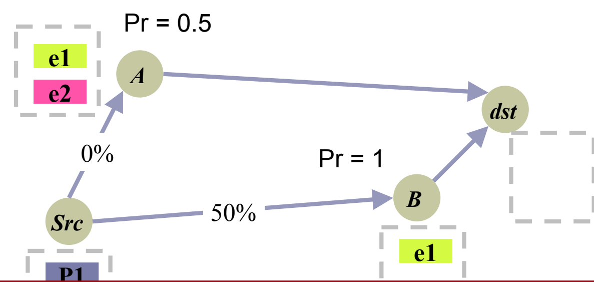
Probabilistic Forwarding



Compute forwarding probabilities without coordination using loss rates

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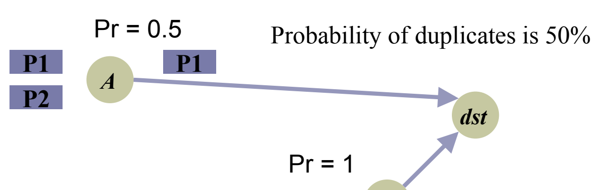
Can ExOR Use Probabilistic Forwarding To Remove Coordination?



- Without random coding → need to know the exact packets to forward every time
- With random coding → need to know only the average amount of overlap

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Adapting to Short-term Dynamics

- Need to balance sent information with received information
- MORE triggers transmission by receptions
- A node has a credit counter
  - Upon reception, increment the counter using forwarding probabilities
  - Upon transmission, decrement the counter
- Source stops → No triggers → Flow is done

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Opportunistic Coding

- Three ways to get neighbor state
  - Reception report
  - Guess
    - Based on ETX metric (delivery probability)
    - Estimate the probability that packets are overheard
  - The neighbor is the previous hop of the packet

COPE Design

- Pseudo Broadcast
  - Cons of broadcast
    - Unreliable due to no ACK
    - Lack of backoff
  - Piggy back on unicast
    - Set one of intended node as Mac address
    - List all others in COPE header (between MAC and IP header)
    - Receiver: if it is on the list, decode the packet, else store the packet in its pool