Random-Packet CDMA: A Novel Wireless Packet System

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Random Packet Communications

For packet services, random access provides fundamental advantages

Advantages:
- Random access is self regulating
- Random access is load-adaptive
- Random access is resource economical
- Random access simplifies infrastructure

Channel State Knowledge is Needed:
- Load regulating is required
- Channel load sensing is needed
- A return channel is required

Triumphs of Random Packet Access:

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Norm Abramson's ALOHA</td>
</tr>
<tr>
<td>1976</td>
<td>EtherNet</td>
</tr>
<tr>
<td>1980</td>
<td>IEEE 802.3 standard</td>
</tr>
<tr>
<td>1990</td>
<td>Spread ALOHA</td>
</tr>
<tr>
<td>1997</td>
<td>Carrier-Sense Multiple Access (CSMA)</td>
</tr>
<tr>
<td>2000+</td>
<td>IEEE 802.11</td>
</tr>
<tr>
<td></td>
<td>AlohaNet</td>
</tr>
<tr>
<td></td>
<td>3G Networks</td>
</tr>
</tbody>
</table>

Aloha is the original random access protocol

Packet 1
Packet 2
Packet 3
Packet 4

Collision eliminates both packets
Time

The maximum throughput of ALOHA is

\[ S = G \exp(-2G) \rightarrow 0.18 \]

(only 18% of a fully coordinated system)
Modulation for Wireless Access

Code-Division Multiple-Access (CDMA)

CDMA uses spread-spectrum (SS) signals with unique signature sequences for different users.

An SS signal is one whose Fourier bandwidth is much larger than its information bandwidth.

CDMA:
- allows the co-existence of signals on the same channel
- provides a virtually unlimited number of signature sequences
- is a beginin technology (IS95, CDMA2000)
- CDMA is insensitive to interference
- CDMA is sensitive to unequal received power levels

Spread ALOHA is combination of ALOHA with CDMA

Packet 1
Packet 2
Packet 3
Packet 4

Collision eliminates both packets

Time →

After despreading, one essentially obtains classical ALOHA

\[ S = G \exp(-2G) \rightarrow 0.18 \]

Joint Detection for Random Packet
CDMA becomes a necessity
Novel Packet Format for Random Access

**Packet Structure**
consists of a distinct header and a (flexible) data portion

<table>
<thead>
<tr>
<th>Access Preamble</th>
<th>Code ID</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame 1: Header</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame 2: Data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**System Effect:** The particular novel packet format effectively separates the communications into a Header Channel and a Data Channel

- **Header Channel**
  - Predetermined
  - Common to all
  - Block encoded
  - Common spreading code
  - Collision limited
  - Multiuser detection
  - 2000-20000 bits

**System Characteristics:**

- The **Header Channel** is essentially a low-traffic spread ALOHA channel
- The **Data Channel** needs to be able to handle a possibly large number of concurrent packet transmissions, this may require joint detection to approach the capacity limit of the medium

The ratio of header length $L_h$ to data portion length $L_d$ is a crucial parameter for this system. We choose

$$\frac{L_h}{L_d} = \frac{200\text{bits}}{MTU} = \frac{1}{60}$$

where MTU is the **Maximum Transmission Unit** of the Ethernet equalling 12,000 bits.
Receiver Requirements

For high performance receivers rely on advanced technologies researched at the HCDC

**Header Channel:** is in its essence a spread-ALOHA channel with very small load, hence the throughput is essentially equal to the offered load

**Data Channel:** consists of overlapping concurrent data packets with different signature sequences. Its efficient detection requires an advanced joint detection receiver.

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**Header Despreading** turn channel into a low-traffic ALOHA channel:

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Results for Equal Power System with Poisson Arrivals

Example Values for a system with spreading gain \( N = 60 \), with a joint detector capability of \( K = 20, 60, 120 \).

**Throughput Curves:**
Throughput achievable with different levels of detector capability

**Packet Loss Probabilities:**
Loss as a function of header collisions and detector failure

The throughput degradation or the packet loss are only minimally effected by header collisions – This system is no longer collision limited, it is channel limited.
Advanced Joint Detection Receivers

Some Facts:

- Joint Detection is easier with unequal received power levels
- Simple Cancellation receivers are sufficient to approach the channel capacity of the multiple access channel [ScShBu04]

Adaptive Rate Finding Algorithms — Dynamics

Since the maximal transmission rates are not known, rate-finding mechanisms need to be used.

**Simple Rate Finding Algorithm:**

1. **Node 1**
   - send packet at rate *x*
   - WAIT
   - Increase rate by some increment
   - send packet at increased rate
   - calculate channel or detector capacity limit for the chosen rates
   - ACK, sri
   - send packet at rate *x*
   - calculate channel or detector capacity limit for the chosen rates

2. **Base Station**
   - calculate channel or detector capacity limit for the chosen rates
   - Sum of chosen rates is below system capacity
   - fair shares of each node
   - send packet at rate *y*
   - ACK, sri
   - send packet at increased rate
   - calculate channel or detector capacity limit for the chosen rates

3. **Node n**
   - send packet at rate *y*
   - WAIT
   - Increase rate by some increment
   - send packet at increased rate
   - calculate channel or detector capacity limit for the chosen rates

**Channel Utilization:**

Each packet brings along a capacity increase in the channel of the amount

\[
\Delta C = \frac{1}{2 \ln(10)} \Delta P \frac{\Delta P}{1 + P/N}
\]
Example Scenarios

Capacity simulations for a network with a central hub station and equal power terminal nodes generating traffic according to

**A Poisson Packet Arrival Process:** 10 Nodes with random traffic

![Graph showing Poisson Packet Arrival Process with 92% Capacity]

**A Constant Packet Arrival Process:** 10 Nodes with constant traffic

![Graph showing Constant Packet Arrival Process with 95% Capacity]

The total information theoretic capacity of a random CDMA channel is

\[ C = \log \det \left( I + \rho S^T S \right); \quad S: \text{spreading sequence matrix} \]
Outlook

For its successful realization, a number of components are still required:

- Reliable low-SNR header timing detection
- Successful joint detection via signal cancelation of many signals
- System study on realistic channels with different received power levels
- Integration into higher order protocols
- Extension of the design and performance studies to ad-hoc networks
- Hardware prototyping of enabling technology is under way