Multi-user Acoustic Communications:

CDMA Receiver Design and Experimental Demonstration

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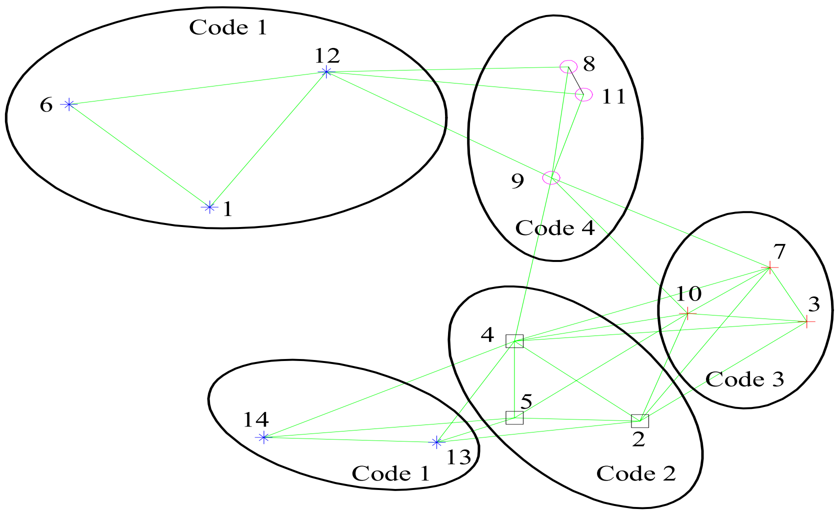
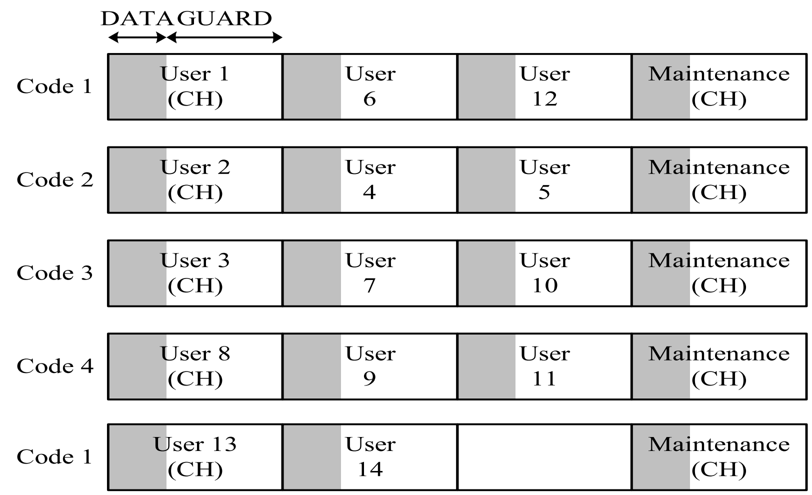
Motivation





- DS-SS offers a platform for scalable acoustic networking using CDMA (multipath diversity, soft capacity, LPI/LPD)
- Several autonomous users, few kilometers
- Goal: wideband acoustic CDMA system design and demonstration (multichannel adaptive detection)

Overview

- Problem formulation:
  - existing solutions for multiuser detection in time-varying multipath channels (radio)
  - limitations for use in underwater acoustic channels
- Detection algorithms:
  - Symbol Decision Feedback (SDF)
  - Chip Hypothesis Feedback (CHF)
- Experiment: AOFNC (Elba, Italy, 2003)
  - 4 users, 2 km
  - 20 kchip/sec, QPSK, varying spreading factor

Problem formulation

- DS-SS: one symbol=L chips (L=T/Tc is spreading factor)
- Existing radio systems:
  1. interchip interference exists, but intersymbol interference can be neglected (Tm<<T)
  2. time-variation negligible, phase stable over one symbol (fdT<<1)
- Conventional system design:
  despreading for multiuser interference suppression
- Wideband radio systems (1 no longer holds, but 2 does):
  - include equalization for multipath interference suppression
  - adaptive filtering at symbol rate

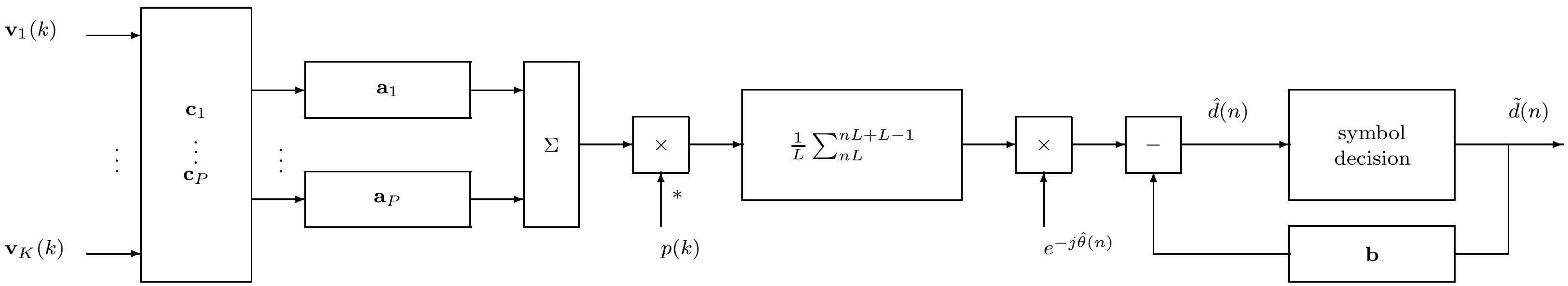
Wideband acoustic system design

- Full bandwidth utilization:
  - transmit at maximal chip rate (Rc$\sim$ B, Tc=1/Rc is fixed)
  - choose spreading factor L to support desired number of users, but maximize data rate (R=Rc/L is downscaled)
- B $\sim$ 10 kHz $\rightarrow$ L $\sim$ few tens
- Multipath (Tm $\sim$ 10 ms):
  - spans tens of chips, exceeds symbol duration
  - necessitates decision-feedback equalization
- Time-variability (fd=fc (v/c), v $\sim$ few m/s):
  - e.g., fc=30kHz, Rc=20 kchip/sec $\rightarrow$ fdT $\sim$ 0.001 vL
  - time-variation not negligible, phase not stable over one symbol (neither assumption holds)

Detection algorithms

- Single-user detection (low complexity)
- Multichannel (array) processing: many-to-few combiner
  [Stojanovic et al., "Reduced-complexity multichannel processing...," JASA, Aug. '95]
- Decision-feedback equalization:
  - feedforward filtering: chip resolution
  - feedback filtering: symbol/chip resolution
  - adaptation rate: symbol/chip

Receiver design: Symbol Decision Feedback (SDF)

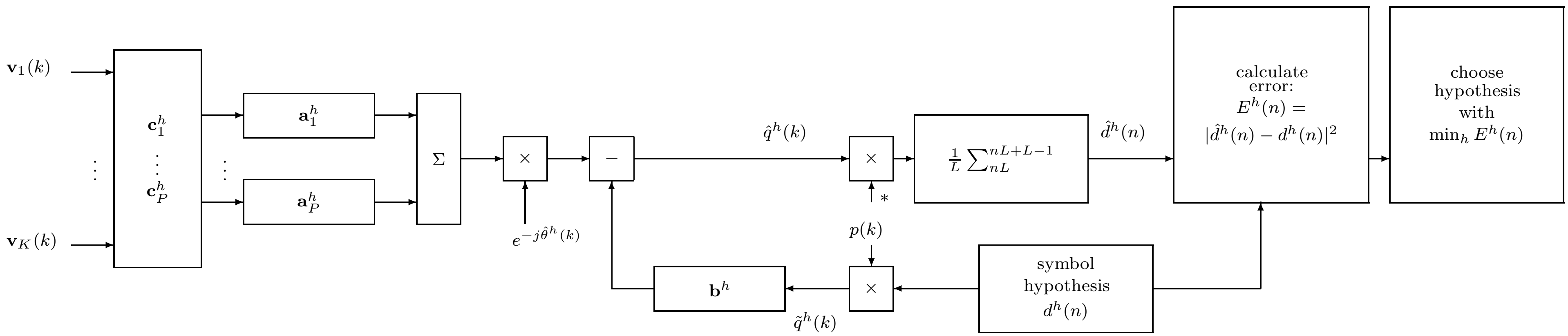


- Related work: [Abdulrahman et al., "Decision feedback... indoor wireless communications," IEEE JSAC, May '94]
- Fractionally (chip) spaced feedforward filter, symbol-spaced feedback filter (M∼ Tm/T)
- MMSE adaptation driven by symbol error $[d(n) - \hat{d}(n)]$: combiner, equalizer, phase estimator (RLS/LMS/DDPLL2).
- SDF: low complexity (+) slow tracking (-)

Performance vs. spreading factor

- Problem:
  - When L increases, and B is fixed, symbol duration increases.
  - Longer symbol, greater channel variation over it, worse performance of symbol-rate tracking.
- Performance should <u>not</u> deteriorate when spreading factor is increased. (On the contrary, it should improve).
- Solution: chip-rate tracking.

Receiver design: Chip Hypothesis Feedback (CHF)

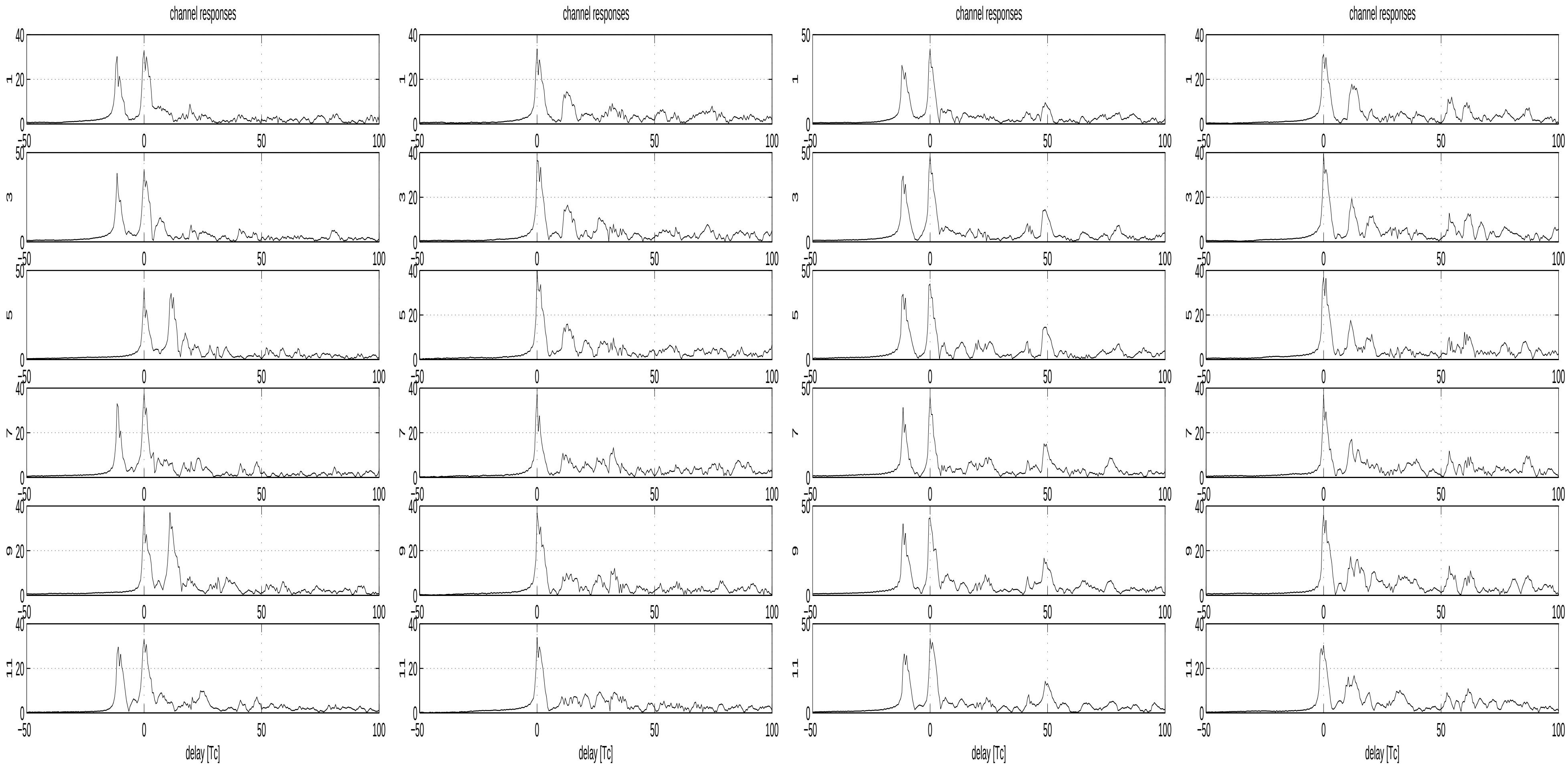


- Related work: [Stojanovic and Freitag, "Hypothesis-feedback... underwater acoustic communications" Proc. Oceans '00.]
- Fractionally (chip) spaced feedforward filter, chip-spaced feedback filter (M $\sim$ T/Tc)
- MMSE adaptation driven by chip error $[q(n) - \hat{q}(n)]$: combiner, equalizer, phase estimator (LMS/LMS/DDPLL2).
- CHF: higher complexity (-) fast tracking (+)

Experiment

- Four users, QPSK modulation
- Chip rate 19.2 kchip/sec, root raised cosine shaping (0.25)
- Kasami spreading codes L=15, 63, 255
- Per-user data rate: 2500, 600, 150 bps
- Aggregate throughput: 10, 2.4, 0.6 kbps
- Carrier: 33 kHz, bandwidth 21-45 kHz
- Sampling rate: 96 kHz (Matlab wave files)
- Elba '03: sequential transmission, same location, no mobility
- Range 2.3 km, depth $\sim$ 100 m
- Rx array: 12 elements (0.15 m), at 30 m

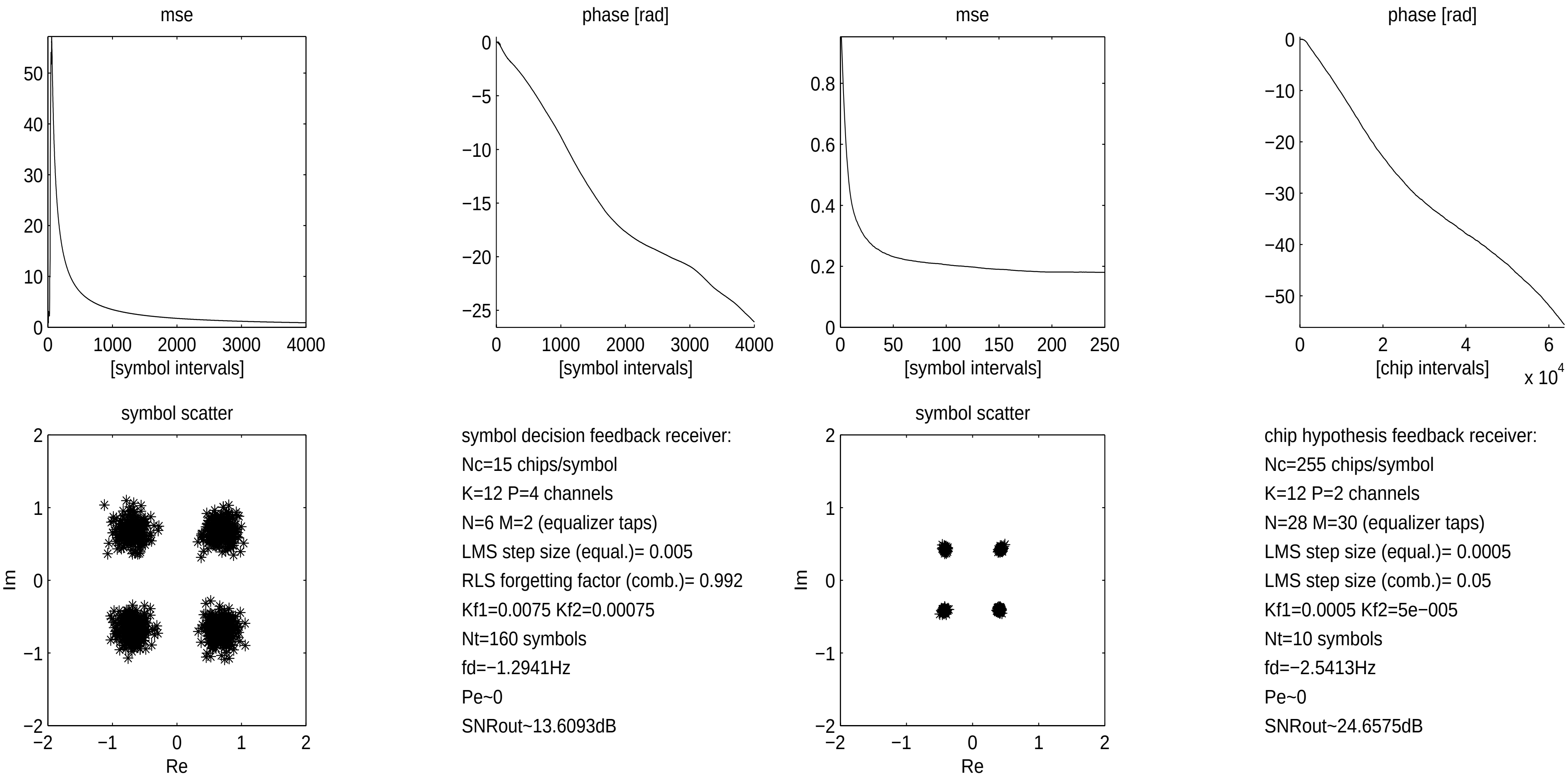
Channel response in space and time



Estimates are obtained by matched filtering to the frequency sweep channel probe.

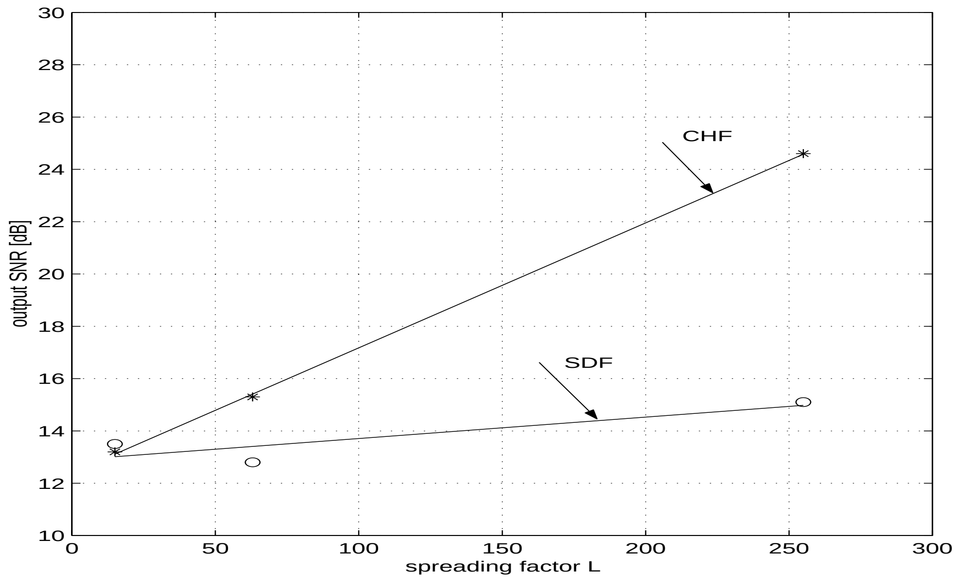
Snapshots are taken at 0.3 m (vertical spacing) and 24 s (time between packets).

Performance illustration: SDF at L=15 and CHF at L=255



All the users have equal power. Interferers arrive asynchronously (at 8, 4, 2 chips delay).

Performance summary



- Wideband acoustic communications (Rc=B): Trade-off between processing gain and tracking capability in classical design (SDF) can be eliminated by chip-rate adaptive processing (CHF).
- Good performance of both receivers owes to the use of multi-channel combining.

Conclusions

- **Experimental results**:
  - Small number of users (4) well supported at minimal bandwidth expansion (L=15) using simple SDF.
  - At high bandwidth expansion (L=255), CHF offers large processing margin necessary for LPI/LPD applications.
- **Real-time implementation in next generation acoustic modems with CDMA**:
  - Single-user detection with multichannel (array) combining.
  - Use SDF when channel variation is tractable at symbol rate (low L). SDF has minimal implementation complexity.
  - Use CHF when channel coherence exceeds symbol duration, but chip-rate tracking is possible (large L). CHF complexity increases linearly with modulation level.

- **Future work**: acoustic CDMA communications experiment to include m̲obility and spatial separation of users.
- **Documentation**: [M.Stojanovic and L.Freitag, "Multichannel Detection for Wideband Underwater Acoustic CDMA Communications," *submitted to* IEEE J. Ocean Eng., November 2004.]