A Bandwidth-Efficient Asynchronous Multiple Access Signaling and Coding Scheme

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MULTIMEDIA DATA CHARACTERISTICS

- CONSISTS OF CONTROL INFORMATION AND TRANSFORM COEFFICIENTS
- RUN-LENGTH CODING IS USED
- ERRORS IN CONTROL INFORMATION (USUALLY RUN-LENGTH ENCODED) CAUSES LOSS OF SYNCHRONIZATION AT BEST AND GOBBLEDYGOOK AT WORST
- ERRORS IN TRANSFORM COEFFICIENTS ARE EASILY CONCEALED (IF ERASURE INFORMATION INDICATES WHICH COEFFICIENTS ARE LIKELY TO BE IN ERROR)
- CONTROL INFORMATION IS REDUNDANTLY CODED ON A FRAME-TO-FRAME BASIS SO THAT QUICK SYNCHRONIZATION/ START-UP MAY BE ACHIEVED

PROBLEM OF MULTIMEDIA DATA TRANSMISSION (UNEQUAL ERROR PROTECTION)

PARTITION A MULTI-USER CHANNEL WITH PER-USER CAPACITY, *C*, INTO TWO SUB-CHANNELS, SC_1 AND SC_2, OF CAPACITY C_1 AND C_2 SUCH THAT:

- $C_1+C_2 \approx C$ and $C_1 \sim C_2$
- BER (SC_1) < BER (SC_2)
- LATENCY (SC_1) < LATENCY (SC_2)
- DECODING COMPLEXITY(SC_1)≈DECODING COMPLEXITY (SC_2)

IS THIS POSSIBLE?

APPLICATION: WIRELESS MP3 WALKMANS ACCESSING I-RADIO SITES

OUTLINE

- REVIEW ORTHOGONAL CONVOLUTIONAL CODES (OCCs) ON THE PULSE-POSITION CHANNEL (*Z*-CHANNEL)

- INTRODUCE CODED QPSK WAVEFORMS FOR THE PULSE-POSITION CHANNEL AND DESCRIBE DETECTOR

- SHOW THAT THIS CHANNEL CAPACITY IS TWICE *Z* CHANNEL'S CAPACITY

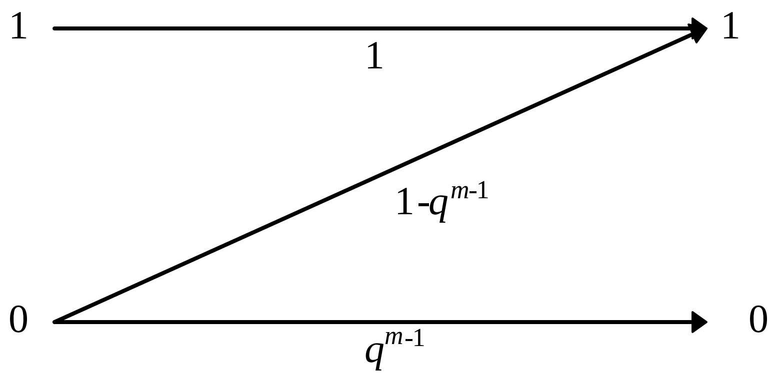
- DECOMPOSE CHANNEL INTO PULSE-POSITION SUB-CHANNEL (PPSC) AND CODE SUB-CHANNEL (CSC)

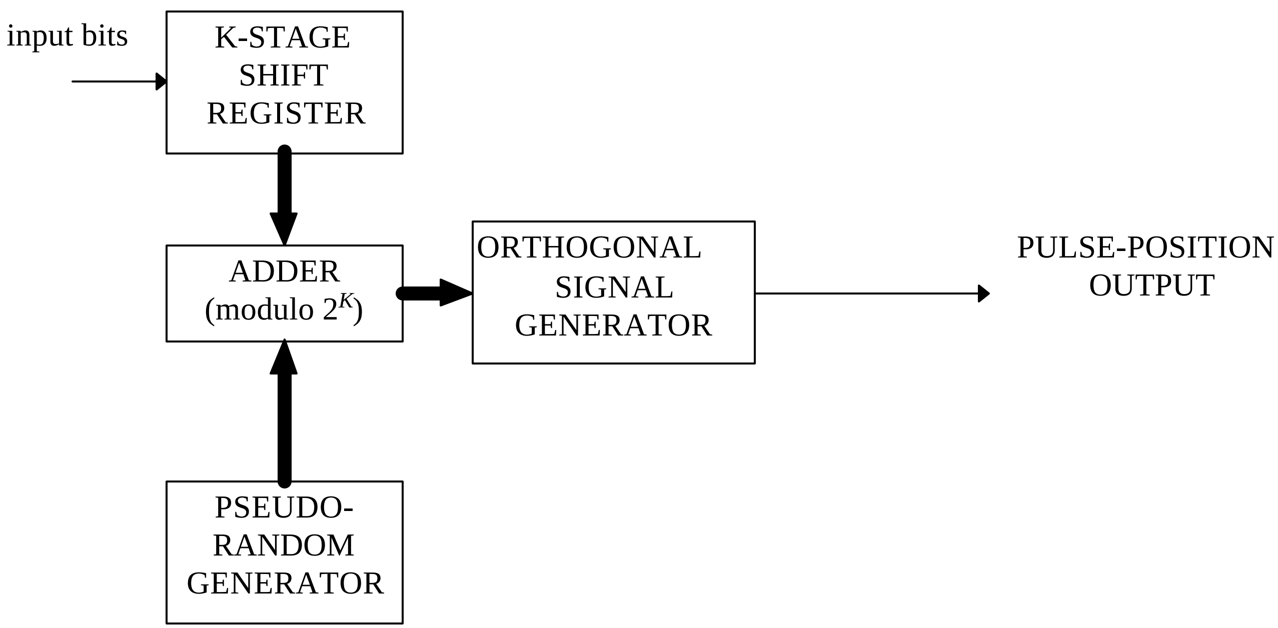
- SHOW THAT BER PERFORMANCE OF PPSC IS BETTER THAN *Z* CHANNEL BY FACTOR OF 6 FOR SAME CODE COMPLEXITY

- SHOW THAT BER PERFORMANCE OF CSC IS A FACTOR OF 10 WORSE THAN PPSC FOR SAME BIT-RATE AND CODE COMPLEXITY (CSC LATENCY IS TWICE PPSC) AND ERASURE INFORMATION CAN BE SUPPLIED TO MULTIMEDIA DECODER

- OTHER ISSUES

Z-CHANNEL AND OCC PULSE POSITION MODULATION (VITERBI AND COHEN 1971)





PERFORMANCE OF PPM SCHEME

- FOR *m*-USERS, CAPACITY PER USER IS ln(2)/*m* (AN EXCELLENT 69.3% EFFICIENCY AS COMPARED TO IDEAL TDM)

- BER PERFORMANCE:

$$P_{B_1} < 0.5 \frac{dT(D,N)}{dN}\bigg|_{N=1, D=D_0} = 0.5 \cdot \frac{(1-P_0)^2 P_0^K}{(1-2P_0)^2}$$

where

$$P_0 = D_0^n = p_m^n = \left[1-(1-2^{-K})^{m-1}\right]^n$$

K=constraint length

m=number of users

MULTIPLEXED NOISE CODES (GOLAY, WELTI, TURYN)

- MNCs ARE SUITABLE FOR ALL VARIANTS OF QPSK
- FORMED BY ORTHOGONALLY MULTIPLEXING CODE PAIRS
- THE APERIODIC AUTOCORRELATION $f_{ab}(t)$ OF THE PAIR (a, b) IS THE SUM OF THE INDIVIDUAL AUTOCORRELATIONS $f_a(t)$ AND $f_a(t)$
- THEY HAVE A SINGLE-VALUED APERIODIC AUTOCORRELATION, I.E.,

$$f_a(t) = -f_b(t)\ ,\ \forall\ t \neq 0$$

WHERE

$$f_a(t) = \sum_{j=0}^{k-1-t} a_j \cdot a_{j+t}$$

CROSS-CORRELATIONS BETWEEN MNC PAIRS

AT LAG t, k-LENGTH SEQUENCES a, b HAVE APERIODIC CROSS-CORRELATION:

$$f_{ab}(t) = \sum_{j=0}^{k-1-t} a_j \cdot b_{j+t}$$

FOR *any* PAIR (i,j) TO BE ORTHOGONAL TO (m,n) AT ALL LAGS, THE APERIODIC CROSS-CORRELATIONS SATISFY:

$$f_{im}(t) = -f_{jn}(t)\ ,\ \forall\ t$$

THIS CONDITION CAN BE MET IFF $(m,n)=(\tilde{j},-\tilde{i})$; FOR ANY k, EXACTLY TWO MNC PAIRS SATISFY THIS

2k LENGTH MNC PAIRS CAN BE OBTAINED FROM k LENGTH MNC PAIRS BY THE GOLAY CONSTRUCTION:

If (a,b) IS MNC, THEN $(ab, a\bar{b})$ IS ALSO MNC (ab IS THE CONCATENATION OF a AND b). $\bar{b}$ IS THE COMPLEMENT OF b. THUS FIND 2 MNC PAIRS $\forall\ 2^s$, s=2,3,….

WHY USE ORTHOGONAL MNC PAIRS FOR MULTIPLE ACCESS?

- 0 AUTOCORRELATION ($t \neq 0$) AND 0 CROSS-CORRELATION WITH THE OTHER MNC PAIR (CARRIER SENSE DOESN'T IMPROVE PERFORMANCE; HOWEVER, RANDOMIZE USERS' TRANSMISSION TIMES).

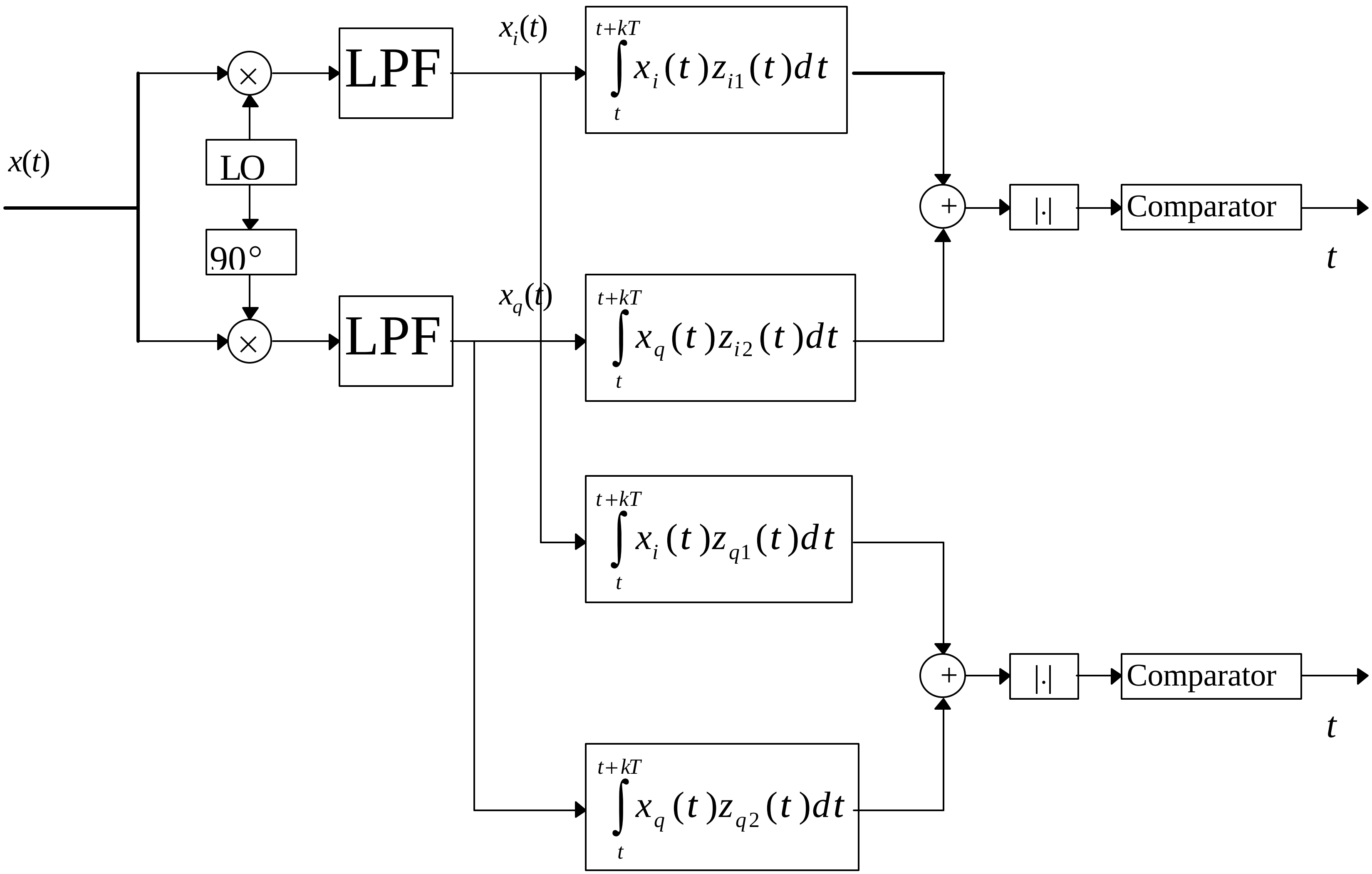
- THE *Z*-CHANNEL SUITS HIGH PEAK-TO-AVERAGE RADIOS; MNCs REDUCE PEAKING REQUIREMENTS.

- INCREASED SIGNAL DURATION DOESN'T REDUCE # SLOTS (MNCs MAY OVERLAP BEYOND A SLOT WITH NO INTERFERENCE). FOR Z CHANNEL, P(QUIET)=$P(z)$=0.5; FOR k-SYMBOL MNC SIGNALING, P(QUIET)=$P(z)^k$.

- ANOTHER OCCUPANCY MEASURE, THE RATIO OF THE STANDARD DEVIATION TO THE MEAN OF SLOT ENERGY, IS $k^{-0.5}$ (I.E., TEMPORAL OCCUPANCY INCREASES BY A FACTOR of 4 for 16 SYMBOL MNC's).

- CW INTERFERENCE DEGRADES PPM DECODING FOR THE *Z* CHANNEL; DOESN'T LIMIT MNC-BASED PPM SYSTEM (THE CROSS-CORRELATION AT 0 LAG IS 0 WHEN CW PHASE IS $lp/2$, $l \in \{0,1,2,3\}$ W.R.T. BAUD).

COHERENT DETECTOR FOR MNC SIGNALING

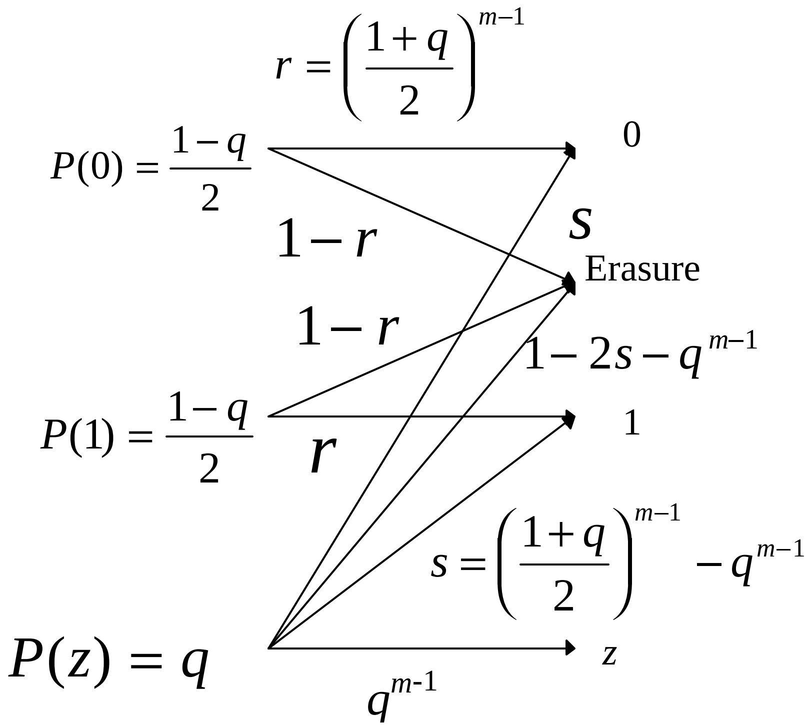


CHANNEL MODEL

- m-USER MULTIPLE ACCESS SYSTEM, EACH USER DATA RATE R, OPERATING BANDWIDTH W, INDEPENDENT TRANSMISSION BY SELECTING TRANSMISSION SLOT AND BETWEEN TWO MNC PAIRS

- IDENTICAL DUTY CYCLE USERS WITH q BEING PROBABILITY THAT A USER DOES NOT TRANSMIT AT A GIVEN SLOT

- CONSIDER ONLY OTHER-USER INTERFERENCE; IGNORE NOISE, MULTIPATH:



Channel transition probabilities; the state *z* represents a quiet channel

CHANNEL CAPACITY

THE CAPACITY, C, OF A K-INPUT, J-OUTPUT, DISCRETE MEMORYLESS CHANNEL, WITH TRANSITION PROBABILITIES $P(j|k)$, $0 \leq j \leq J\text{-}1$, $0 \leq k \leq K\text{-}1$ AND INPUT PROBABILITY ASSIGNMENTS $\boldsymbol{Q}=[Q(0), \ldots, Q(K\text{-}1)]$, IS:

$$C = \max_{Q(0),\cdots,Q(\mathrm{K}\text{-}1)} \sum_{k=0}^{K-1} \sum_{j=0}^{J-1} Q(k) P(j|k) \log \frac{P(j|k)}{\sum_{i=0}^{K-1} Q(i) P(j|i)}$$

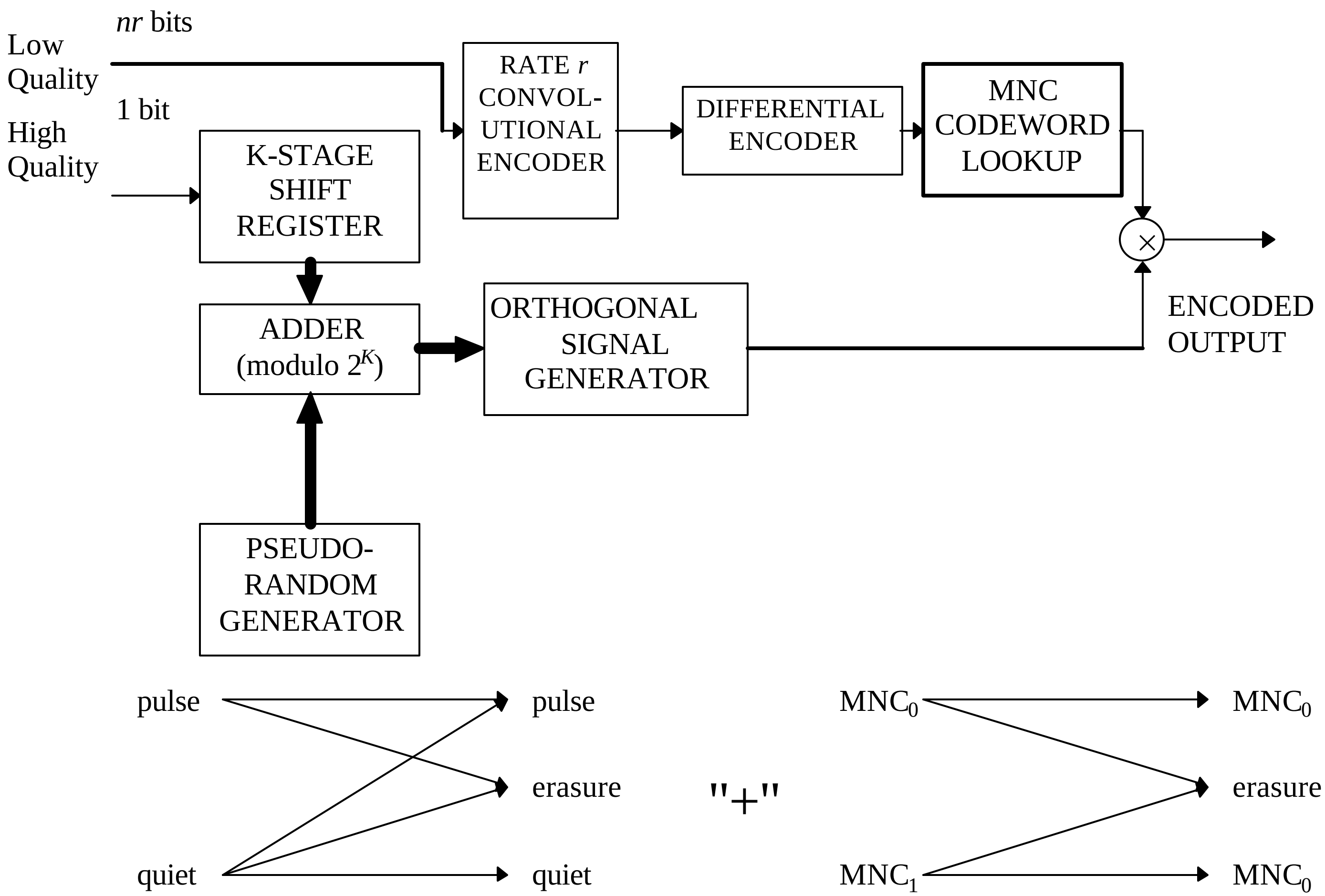
FOR $m >> 1$, OPTIMUM q IS NEARLY 1. FOR $Q(z)=q=1\text{-}k/m$, THE TRANSITION PROBABILITIES ARE $q^{m-1} \sim e^{-k}$, $r \sim e^{-k/2}$, $s \sim \mathrm{e}^{-k/2}\text{-}e^{-k}$, $1\text{-}2s\text{-}q^{m-1} \sim (1\text{-}r)^2$:

$$C \approx -\max_k \frac{k}{m} \log_2 1 - e^{-k/2} = \frac{2 \ln 2}{m} \qquad \text{bits/time slot}$$

CAPACITY IS REDUCED BY ONLY ln2~0.695 RELATIVE TO TDMA USING QPSK AND IS TWICE THAT OF THE Z CHANNEL.

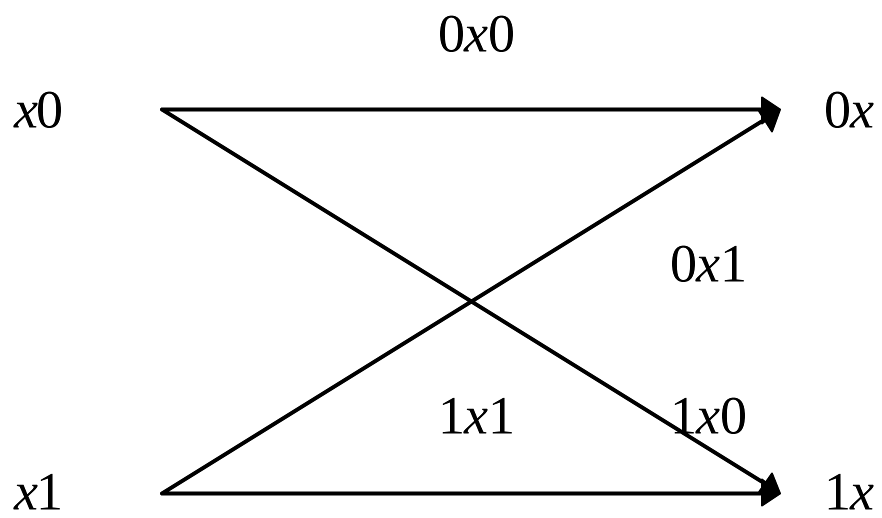
STEADY-STATE PROBABILITIES AT CAPACITY ARE $P(z)=0.5$, $P(0)=P(1)=(\sqrt{2}\text{-}1)/2$, AND ERASURE PROBABILITY IS $2P(0)^2$.

PULSE-POSITION OCC (PPSC) AND CODE SUB-CHANNEL (CSC)



Encoder block diagram

COMPUTATION OF VITERBI DECODER METRICS



State transition diagram

THE OPTIMUM STRATEGY FAVORS PATH WITH ERASURES AS COMPARED TO PULSES RECEIVED WITHOUT ERASURES:

OBSERVE THOSE n POSITIONS FOR THE KNOWN n PULSE (FOR EACH SHIFT REGISTER VALUE, jxi). SET THE BRANCH METRIC R_{jxi} TO # POSITIONS WHERE PULSE AREN'T RECEIVED+$e\times$#MNC's RECEIVED WITHOUT ERASURES ($0<e<1/h$; h IS DECODING HORIZON IN INFORMATION BITS).

PERFORMANCE OF PPSC (1)

q_k : PROBABILITY THAT INCORRECT TIED PATH DIFFERED FROM CORRECT PATH IN k BRANCHES HAS MORE ERASURES THAN CORRECT PATH

$p_k = q_k p_m{}^k$: PROBABILITY THAT INCORRECT PATH IS SELECTED

$$p_a = 1 - \left(1 - \frac{1}{2^{K+1}}\right)^{m-1}$$: ERASURE PROBABILITY | DESIRED PULSE

$$p_b = 1 - 2\left(1 - \frac{1}{2^{K+1}}\right)^{m-1} + \left(1 - \frac{1}{2^{K}}\right)^{m-1}$$: ERASURE PROB. | AN UNDESIRED PULSE

ERASURES IN k-LENGTH CORRECT (N_a) AND INCORRECT (N_b) PATHS ARE BINOMIAL ; WHEN k>>1, APPROXIMATE BY NORMAL DISTRIBUTIONS:

$$f(N) \approx \frac{1}{\sqrt{2pkp(1-p)}} e^{-\left(\frac{N-kp}{\sqrt{2kp(1-p)}}\right)^2}$$

, $N=N_a$, N_b and $p=p_a$, p_b.

PERFORMANCE OF PPSC (2)

DISTRIBUTION OF N_b-N_a IS $N[k(p_b-p_a), k\{p_a(1- p_a)+ p_b(1- p_b)\}]$. THE ERRONEOUS PATH IS SELECTED WHEN N_b-N_a >0 AND WITH PROBABILITY 0.5 WHEN N_b-N_a=0 AND THIS PROBABILITY, q_k:

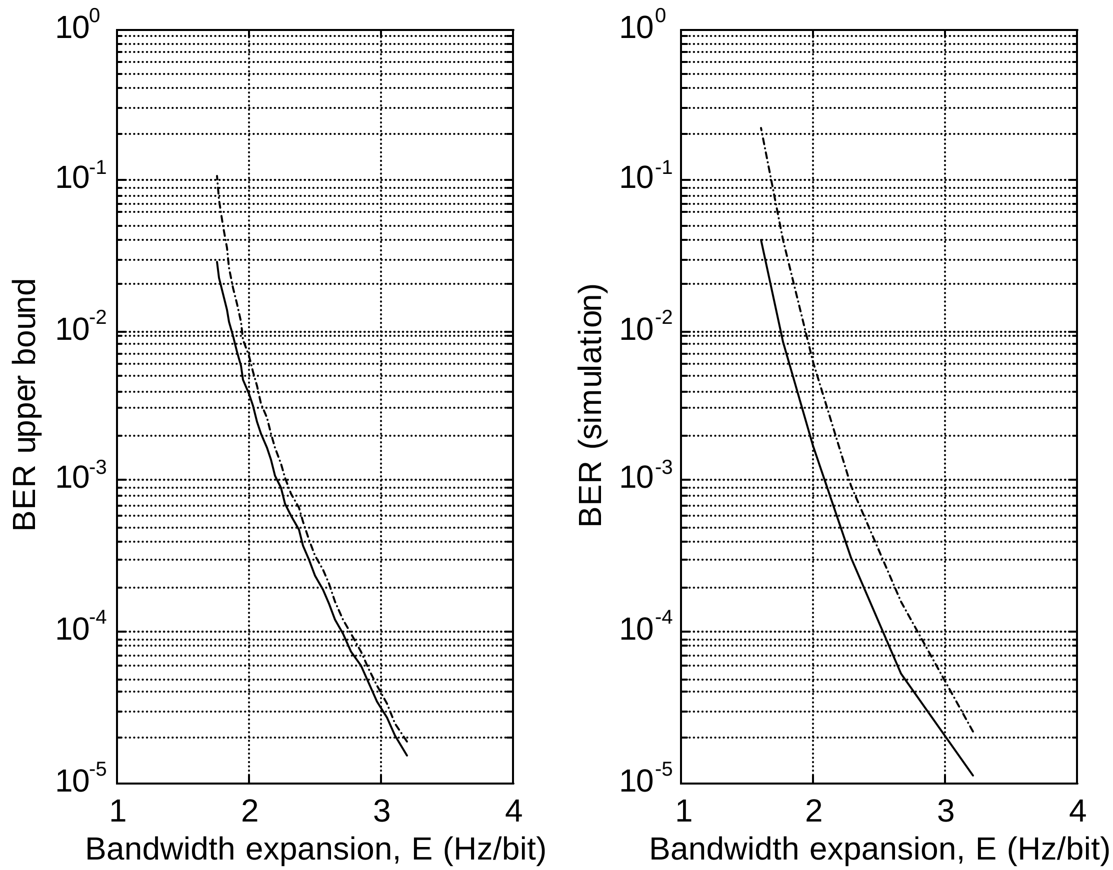
$$q_k \approx erfc \frac{k(p_a - p_b)}{\sqrt{k\{p_a(1-p_a)+p_b(1-p_b)\}}} \text{ where } erfc(x) = \frac{1}{\sqrt{2p}} \int_x^{\infty} e^{-\frac{x^2}{2}} dx .$$

q_k HAS AN UPPER BOUND (FOR p_a>p_b):

$$q_k < e^{\frac{-k(p_a-p_b)^2}{2\{p_a(1-p_a)+p_b(1-p_b)\}}}$$

$$P_{B_1} < \frac{(1-P'_0)^2 P'^K_0}{(1-2P'_0)^2} \text{, where } P'_0 < \left[e^{-\frac{(p_a-p_b)^2}{2\{p_a(1-p_a)+p_b(1-p_b)\}}} \cdot \left[1-\left(1-2^{-K}\right)^{m-1}\right]\right]^n$$

COMPARISON OF UPPER BOUND AND SIMULATED PERFORMANCE WITH Z CHANNEL



Comparison of *n*=2, *K*=7 PPSC performance with (lower traces) and without (upper traces) erasure processing. The inequality used in approximating q_k results in a tight upper bound at low bandwidth expansions.

CHANNEL CODING FOR CSC

nK-LENGTH ERROR/ ERASURE BURST (AT ERRONEOUSLY PPSC DECODED POSITIONS) AND RANDOM ERASURES AT RATES P_{B_1} AND p_a OCCUR ON THE CSC. HARD DECISION DECODING BER IS:

$$P_{HD(CSC)} = 0.5(nKP_{B_1} + p_a) \approx 0.5 p_a$$

THIS ERROR-RATE IS UNACCEPTABLE (e.g., 0.195 for K=7, m=128).

ASSUMING CONVOLUTIONAL CODING, IF CSC PPSC ARE TO HAVE SAME ERROR EXPONENTS, THE CSC's CODE REQUIRES A MUCH HIGHER (IMPRACTICAL) CONSTRAINT LENGTH THAN THE PPSC.

PERFORMANCE OF CSC VITERBI DECODER

- FOR ERASURE CHANNELS, ONLY TIES CAUSE ERRORS
- USE MAJORITY-LOGIC TIE RESOLUTION.
- AN ERASURE OUTPUT ACCOMPANIES EACH VITERBI DECODED BIT

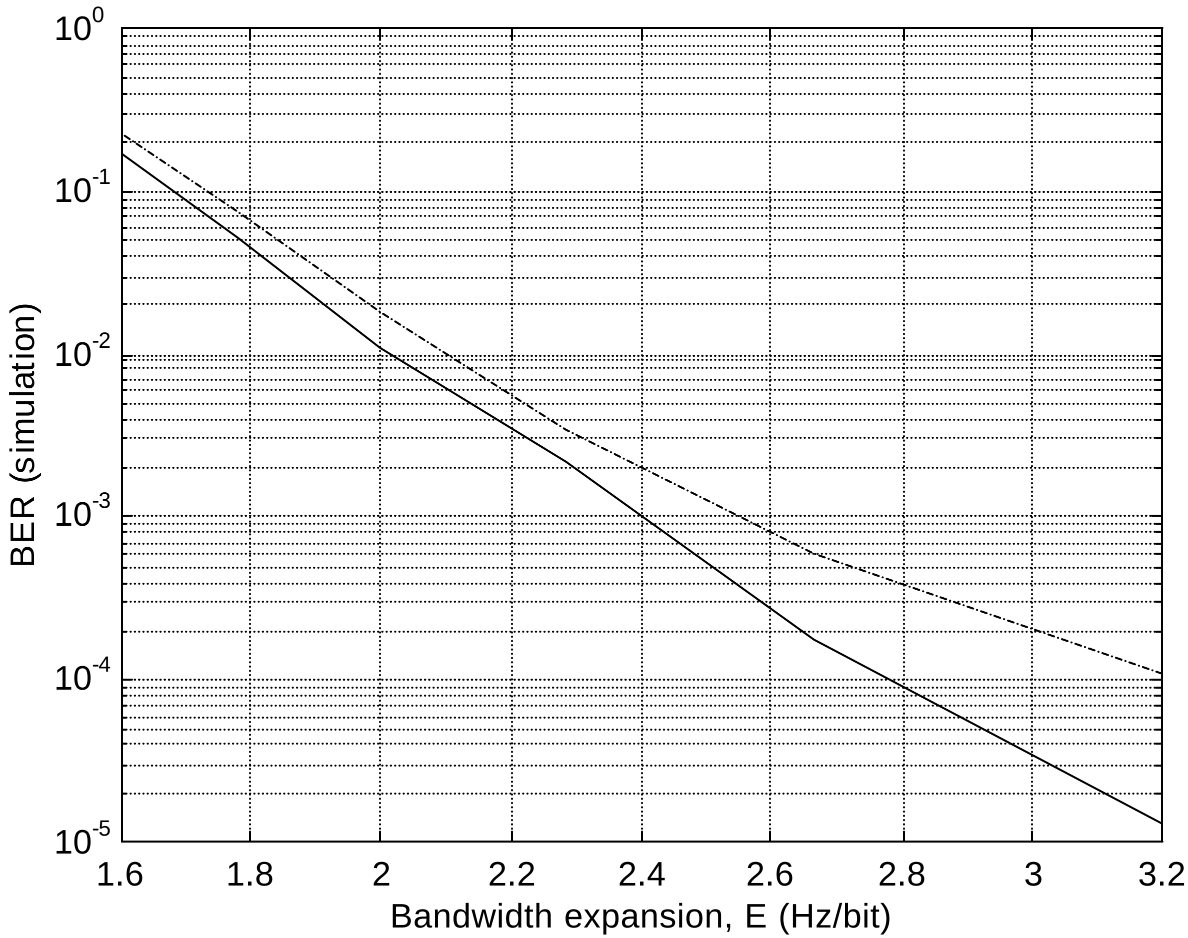
TIES REMAIN UNRESOLVED (i.e., OUTPUT ERASURE) FOR MULTIPLE WINNING PATHS *and* WHEN CARDINALITY OF WINNING PATH SUBSETS YIELDING 0 AND 1 ARE EQUAL. AN UPPER BOUND OF THE CSC's BER, FOR A FAR DECODING HORIZON, IS THE PRODUCT OF FORWARD AND BACKWARD WINNER TIE PROBABILITIES:

$$P_{B_2} < \left[\left. \frac{dT(D,N)}{dN} \right|_{N=1, D=p_a} \right]^2$$

$T(D,N)$ IS THE GENERATING FUNCTION FOR THE AUGMENTED CONVOLUTIONAL CODE STATE DIAGRAM. THE CSC BER UPPER BOUND IS:

$$P_{B_3} < P_{B_1} \frac{nK}{2} + (1 - P_{B_1}) P_{B_2}$$

SIMULATED ERROR AND ERASURE RATES OF CSC



CSC error (upper trace) and erasure (lower trace) rates with K_{CSC}=7, n=2, r=0.5 convolutional code.

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THMA CODE DESIGN

- IF USER DATA IS SIMILAR (FOR EXAMPLE, IN AUDIO COMPRESSION, QUANTIZATION INDICES, SCALE FACTOR, ETC. DURING QUIET PERIODS), THEN FHMA (e.g., REED-SOLOMON, NO) CODES MAY BE USED FOR THMA TO INCREASE MULTIPLE-ACCESS PERFORMANCE

- EVEN IF USER DATA IS RANDOM, THERE IS NO HARM IN USING FHMA CODES

- THMA CODE GENERATOR IS STEPPED n TIMES PER USER SYMBOL INTERVAL

CODE ACQUISITION

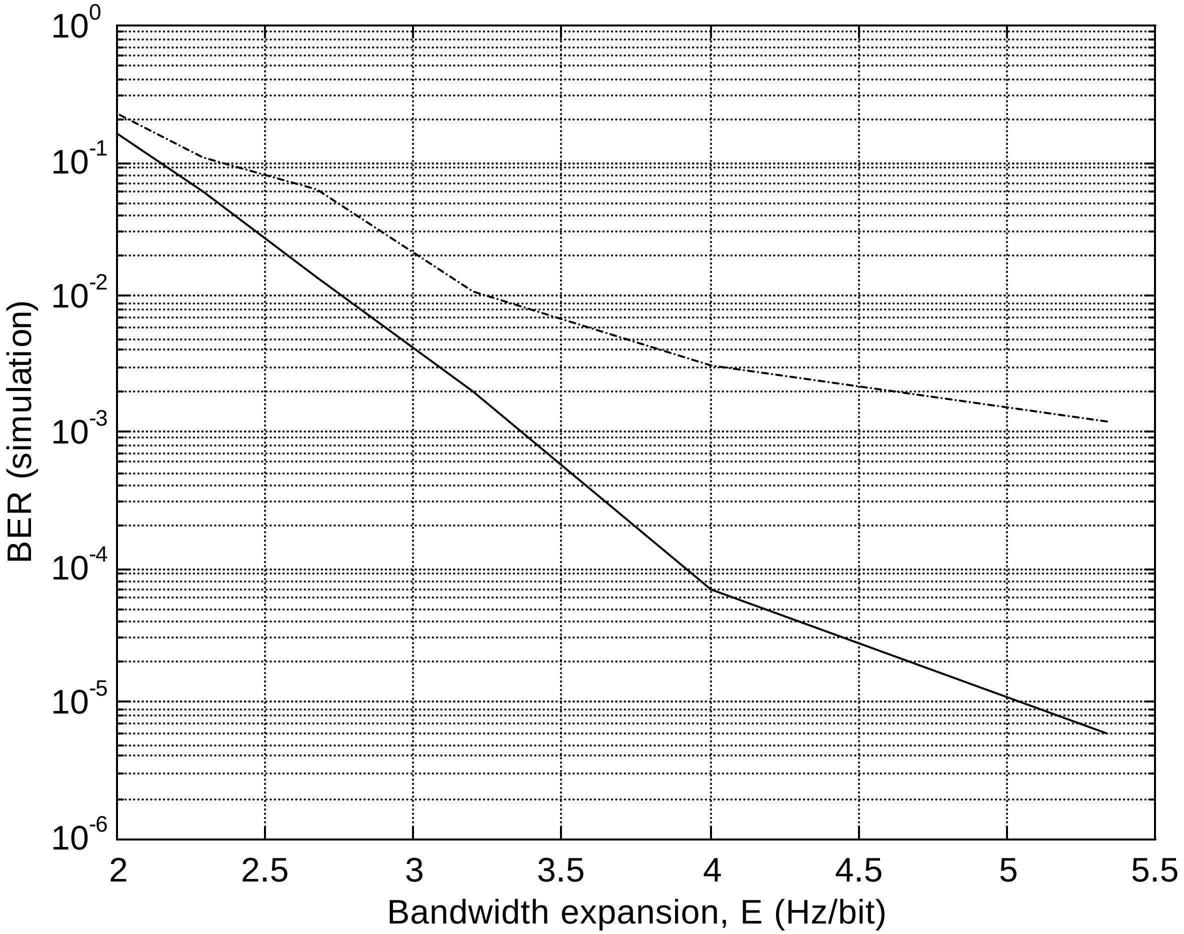
- HIGHLY STABLE TOD STANDARDS AND FIXED TIME INDEXING ASSUMED
- CODE ACQUISITION VIA PPSC VITERBI NODE SYNCHRONIZATION
- EACH NUMBERING IN PPM IS A COSET OF THE THMA CODE
- EACH OF L COSETS EXAMINED TWICE, ONCE PER 1/2 TIME STEP
- L IS DETERMINED BY MAX. CLOCK UNCERTAINTY AND PROP. DELAY
- IF GUARD TIME=Lt, $L/(n2^K+L)$ IS THE OVERHEAD -TO-PAYLOAD RATIO
- L LIMITS MAX. USER BIT RATE TO $(1+nr)\cdot(Lt)^{-1}$ bps, (t : CHIP DURATION)
- TRANSMITTER BIT TIMING IS TRACKED USING AN EARLY-LATE GATE ON THE REGENERATED CODE FROM THE OUTPUT OF THE CSC VITERBI DECODER AND A DELAYED VERSION OF THE RECEIVED SIGNAL

PHASE AMBIGUITY RESOLUTION

- CARRIER PHASE AMBIGUITY OF *p* IS RESOLVED BY TAKING THE ABSOLUTE CORRELATOR OUTPUT PRIOR TO THRESHOLDING (FIGURE 2)
- FOR ±*p*/2, MNC (i,j) BECOMES (-j,i) AND (j,-i)
- WHEN THE RECEIVED SIGNAL (-j, i) IS CORRELATES WITH $(\tilde{j}, -\tilde{i})$, THUS CAUSING A 1 TO BECOME 0 AND VICE VERSA
- DIFFERENTIAL ENCODING ON CSC CHANNEL REQUIRED
- PREAMBLE AIDS QUICKER NODE SYNCHRONIZATION
- CODE PHASE DWELL TIME ~ TIME TAKEN BY PPSC VITERBI DECODER TO DECLARE NODE SYNC. (IF PRESENT)

EFFECT OF DESTRUCTIVE INTERFERENCE

MODEL AS DELETION-PROBABILITY ON INTERFERENCE



PPSC (upper trace) and CSC (lower trace) error rates (without differential decoding) for K_{PPSC}=7, K_{CSC}=7, *n*=2 and *r*=1/6.

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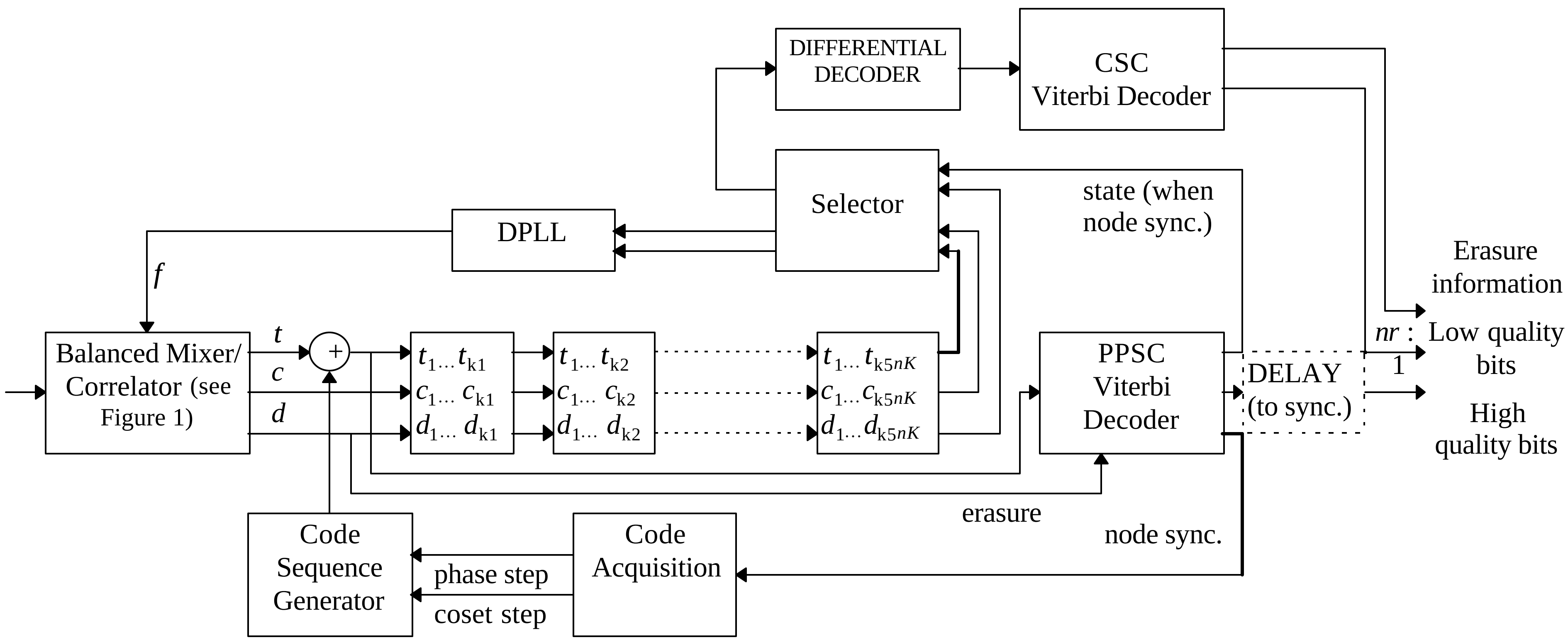

Receiver Signal Processing

REJECTION OF MULTIPATH COMPONENTS

- IF MULTIPATH COMPONENT ARRIVES > 1 CHIP WAY, IT IS REJECTED BECAUSE CODE IS RANDOMIZED

- SINCE TRANSLATES OF THE CODE PATTERN ARE EXAMINED IN INCREASING ORDER DURING CODE ACQUISITION, MULTIPATH LOCK OCCURS ONLY IF ACQUISITION FAILS ON DIRECT COMPONENT

- IN THE LATTER CASE, CHANGE IN MULTIPATH MAY CAUSE LOSS OF SYNCHRONIZATION, IN WHICH CASE THE DIRECT SIGNAL PATH WILL BE ACQUIRED WITH HIGH PROBABILITY

CONCLUSIONS

- IMPROVED SPECTRUM UTILIZATION
- RESISTANCE TO CW INTERFERENCE
- RESISTANCE TO SIMILAR SIGNAL INTERFERENCE
- IMPROVED TIME OCCUPANCY
- IMPROVED PERFORMANCE DUE TO ERASURE PROCESSING

SEVERAL IDEAS AND RESULTS HAVE BEEN PRESENTED:

- ASYNCHRONOUSLY USING A PAIR OF ORTHOGONAL (AT ALL LAGS) MNCS FOR SIGNALING
- REGISTERING CANDIDATE PULSES WITH COHERENT CORRELATORS
- ERASURE PROCESSING TO MITIGATE CO-CHANNEL INTERFERENCE
- CHANNEL MODEL AND CHANNEL CAPACITY FOR THIS SCHEME
- A BER UPPER BOUND FOR THE PULSE-POSITION SUB-CHANNEL AS A FUNCTION OF BANDWIDTH EXPANSION FACTOR
- THE USE OF THE CSC FOR MULTIMEDIA DATA WHEN DECODERS USE ERROR-CONCEALMENT STRATEGIES
- THE APPLICABILITY OF FHMA CODES TO THE THMA SCHEME GENERATED BY AN OCC
- CODE ACQUISITION AND TRACKING
- PHASE AMBIGUITY RESOLUTION AND CARRIER TRACKING