Vol. 37 No. 7 >pJs=hM}3X2qO@J8;o July 1996

# Aj8_7k9gLV RDT >e$G$N3,AX%^%k%A%-%c%9%H$K$h$k %a%b%j%3%R!<%l%s%70];}<jK!

@> B< 9n ?† . 9) F# CN 9†† ( @> 9( >† 0
ML 6r O† % E7 Ln 1Q @† 2

9qFb 7 Bg3X$G6&F13+H/Cf$ND6JBNs7W;;5! JUMP-1 $O!$J,;66&M-%a%b%j$r;}$A RDT!J *Recursive Diagonal Torus*!K$H8F$VLZ9=B$$rFbJq$9$k%/%i%9%?4V7k9gLV$rMQ$$$k!%LZ9=B$$rFbJq$9$k7k9gLV$G$O!$%a%b%j%3%R!<%l%s%70];}$N$?$a$K3,AXE*$K%G%#%l%/%H%j$r9=@.$9$k3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$rMQ$$$k$3$H$,$G$-$k!%$3$NJ}<0$G$OMM!9$J%G%#%l%/%H%jD9=LLsK!$rMQ$$$k$3$H$,$G$-!$JUMP-1 $GMQ$$$i$l$kJ}<0$O$=$N0l<o$G$"$k$H9M$($k$3$H$,$G$-$k!%K\O@J8$G$O!$3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$rDj5A$7!$JUMP-1 $GMQ$$$i$l$kJ}<0$N RDT >e$G$N<B8=K!$r<($7$F$=$N%G%#%l%/%H%j=LLsJ}<0$H$7$F$N@-G=$rI>2A$9$k!%$^$?!$RDT %k!<%?%A%C%W$N9=@.$K$D$$$F=R$Y$k!%

# Memory coherency control schemes on the RDT interconnection network

Katsunobu.Nishimura,† Tomohiro.Kudoh,†† Hiroaki.Nishi,†
Yulu.Yang† and Hideharu.Amano†

JUMP-1 is currently under development by seven Japanese universities to establish techniques of an efficient distributed shared memory on a massively parallel processor. It provides a memory coherency control scheme called the *hierarchical bit-map directory* to achieve cost effective and high performance management of the cache memory. Messages for maintaining cache coherency are transferred through a fat tree on the RDT (Recursive Diagonal Torus) interconnection network. In this paper, we discuss on the scheme and examine its performance. The configuration of the RDT router chip is also discussed.

## 1. $O $8 $a $K

6aG/!$0lK|$rD6$($k%W%m%;%C%5?t$r;}$D5,LO$N6&M-$L58z2=7?$H99?77?$,:.:_$9$k=@Fp@-$N9b$$%-%c Ns7W;;5!$K$D$$$F$N8&5f$,MM!9$J8&5f5!4X$K$h$j9T$e%W%m%H%3%k$r<B8=$9$k$3$H$,$G$-$k!% $l$F$$$k!%$3$NCf$G!$J8It>J=EE@NN0h8&5f$N0l4D$H CC-NUMA $N8zN($NNI$$<B8=$rL\;X$9%W%m%8%'%/ $F3+H/$,?J$a$i$l$F$$$kD6JBNs7W;;5!%W%m%H%?%$%W $K$O!$B>$K$b Stanford-FLASH and MIT-Alewife[2] JUMP-1[13),15)] $O!$%-%c%C%7%e$rMQ$$$?J,;66&M-%a%b$J$I$,$"$k!%$3$l$i$N%W%m%8%'%/%H$O!$$$$:$l$b5,LO %j!J Cache Coherent Non Uniform Memory Access $K0MB8$7$J$$%9%1!<%i%V%k$J%7%9%F%`$rL\;X$7$F$$$k model: CC-NUMA!K$r!$D6JBNs7W;;5!>e$K8zN(NI$$,!$6qBNE*$KA[Dj$7$F$$$k:GBg5,LO$O?tI4%W%m%;%C%5 <B8=$9$k$3$H$rL\;X$7$F$$$kE@$KFCD'$,$"$k!%$3$N DNEY$G$"$k!%$3$N$?$a!$$3$l$i$N%7%9%F%`$G$O%-%c%C E*$N$?$a!$JUMP-1 $O?^ 1 $K<($9 4 $D$N RISC %W%m %7%e%G%#%l%/%H%j$r%i%$%sC10L$G4IM}$7!$L58z2=7?$N %;%C%5$+$i@.$k%/%i%9%?9=B$$r;}$A!$3F%/%i%9%?$O $W%m%H%3%k$K$h$j%-%c%C%7%e$N0lCW$r@)8f$7$F$$$k!% MBP[16),17)] $H8F$P$l$kJ,;6%a%b%j!$$*$h$S%a%C%;!<$3$l$NJ}K!$OMM!9$JI>2A$d<B%7%9%F%`>e$G$N<B8[6)] $N7P83 DL?.$N4IM}$r9T$&@lMQ:YN3EY%W%m%;%C%5$K$h$j!$A4$$?t==$+$i?tI4$N5,LO$J$i$P9b$$8zN($rF@$i$l$k$3 $H$,L@$i$+$K$J$C$F$$$k!%

$3$l$KBP$7!$JUMP-1 $O%W%m%;%C%5?t$,0lK|$rD6$( $k5,LO$rA[Dj$7$F$$$kE@$,0[$J$k!%$3$N$h$&$KBg$-$J 5,LO$N%7%9%F%`$G$O!$%N!<%I$r<1JL$9$k bit ?t$,A}2C $9$k$?$a!$?t==%P%$%HDxEY$NBg$-$5$N%-%c%C%7%e%i%$

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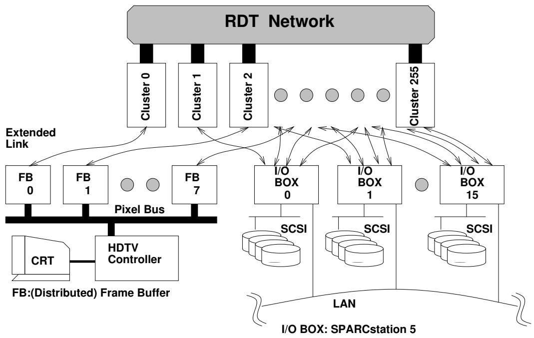
Faculty of Science and Technology, Keio University
†† El5~9)2JBg3X>pJs9)3X2J
Department of Information Technology, Tokyo Engineering University




?^ **1** JUMP-1 $N9=@.
Fig. 1 Structure of JUMP-1.

%s$4$H$K%G%#%l%/%H%j%(%s%H%j$rMQ0U$9$k$H!$%G%#%l%/%H%j$NMFNL$,Bg$-$/$J$j!$9bB.$J%a%b%j$K3JG<$9$k$3$H$,:$Fq$K$J$k!%$5$i$K!$D6JBNs7W;;5!$N;}$DB?7L
$N%W%m%;%C%5$r3hMQ$9$k$?$a$K$O!$99?77?$N%W%m%H%3%k$rMQ$$$F$G!<%?$r@Q6KE*$K6&M-$5$;$k%"%k%4%j%:%`$r3+H/$9$k$3$H$,M-8z$H9M$($i$l$k!%

$=$3$G!$JUMP-1 $G$O!$%Z!<%8!J4 K %P%$%H!K$4$H$K%G%#%l%/%H%j%(%s%H%j$rMQ0U$7!$%G!<%?E>Aw$N$F$r
%i%$%sC10L$G9T$&J}<0$rMQ$$$k!%$5$i$K!$L58z2=7?%W%m%H%3%k$K2C$($F!$99?77?%W%m%H%3%k$N:.:_$r5v$9$k
$H$G!$%G!<%?$r@Q6KE*$KB??t$N%W%m%;%C%5$G6&M-$9$k%"%k%4%j%:%`$r8zN(NI$/<B8=$9$k4D6-$rMQ0U$9$k$3$H$+$7!$$3$N>l9g!$%Z!<%8$r6&M-$9$k%N!<%I!J%/%i%9%?!K?t$O!$%i%$%sC10L$N4IM}$GL58z2=7?%W%m%H%3%k$rMQ$$$k=>Mh$NJ}<0$KHf$Y$FBgI}$KA}2C$9$k2DG=@-$,$"$k!%

$=$3$G!$B??t$N%N!<%I$KBP$7$F!$8zN(NI$/%a%C%;!<%8$rE>Aw$9$k$H$H$b$K!$B??t$N%N!<%I$rI=8=$9$k%G%#%l%/%H%j$NMFNL$b=LLs$9$k$J}K!$,I,MW$K$J$k!%

$3$l$i$rK~B-$9$k<jK!$H$7$F!$>>K\$i$K$h$jDs0F$5$l$?$N$,!$5?;w%U%k%^%C%W%G%#%l%/%H%j[18] $G$"$k!%$3$N<jK!$G$O!$D6JBNs7W;;5!$r9=@.$9$k7k9gLV$N3,AXE*$K%Q%1%C%H$rAw$j=P$9I,MW$,$J$/!$8zN(NI$/%^%k%A%-%c%9%H$9$k!%$3$N$?$a!$Aw?.85$,08@h?t$J$I$GMQ$$$i$l$k3,AX%S%C%H%^%C%W$rM?$($k<jK!$G$"$k!%

$3$N5?;w%U%k%^%C%WJ}<0$O!$LZ9=B$$r$J$97k9gLV$N3,AXE*$K%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$K!$%G%#%l%/%H%jD9$r=LLs$9$k<jK!$rAH$_9g$o$;$?$b$N$H9M$($k$3$H$,$G$-$k!%

3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$OC1=c$JLZ9=B$$N7k9gLV>e$G<B8=$9$k>l9g!$LZ9=B$$N:,85IU6a$G:.;($,M=A[$5$l$k$H$H$b$K!$LZ9=B$$N6-3&%N!<%IIU6a$G%^%k%A%-%c%9%H$KL5BL$,@8$8$k2DG=@-$,$"$k!%$3$NLdBj$r2r7h$9$k$?$a!$JUMP-1 $G$O!$#2<!85%H!<%i%9$N Fat-tree >u$N3,AX9=B$$r;}$D7k9gLV RDT!JRecursive Diagonal Torus!K[19),21)] $rDs0F$7$F$$$k!%

K\O@J8$G$O!$3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$rDj5A$9$k$H$H$b$K!$?7$?$J%G%#%l%/%H%j=LLs[10),12)]$K!$rDs0F$9$k!%$^$?!$$3$N=LLs3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$r RDT >e$K<B8=$9$kJ}<0$K$D$$$F=R$Y!$$5$i$K!$$3$l$i$NJ}<0$NBEEv@-$K4X$7$FM=HwE*$JI>2A$r9T$$!$B>$NJ}K!$HHf3S8!F$$9$k!%

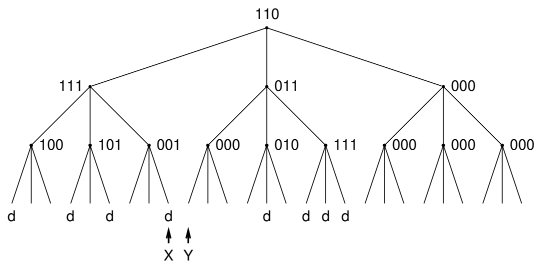
## 2. =LLs3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0

DD>o!$%i%$%sC10L$K%G%#%l%/%H%j$r4IM}$7!$L58z2=7?%W%m%H%3%k$rMQ$$$k>l9g!$L58z2=%a%C%;!<%8$N08@h$O!$1$J$$$7 2$,$[$H$s$I$G$"$k$H$$$o$l$F$$$k[1),2)]!%=>Mh!$%j%_%F%C%I%G%#%l%/%H%jJ}<0$%A%'%$%s%I%G%#%l%/%H%jJ}<0[3),8)]$J$I$N%G%#%l%/%H%j9=@.J}<0$,MQ$$$i$l$F$r$?!%A0<T$O6&M-$7$F$$$k%W%m%;%C%5?t$,0lDj$N?t$r1[$($k$H%V%m!<%I%-%c%9%H$K@Z$jBX$($kJ}<0$G$"$k!%8e<T$O%G%#%l%/%H%j$r%j%9%H9=B$$G;}$A!$$=$N%N!<%I$,;}$A!$6&M-$9$k%W%m%;%C%5$N?t$,%G%#%l%/%H%j?t$rD6$($J$$$h$&$K$9$k$b$N$G$"$k!%

$3$l$KBP$7$F!$%Z!<%8C10L$K%G%#%l%/%H%j%(%s%H%j$r4IM}$7!$99?77?%W%m%H%3%k$rMQ$$$k JUMP-1 $G$O!$%Z!<%8$r6&M-$9$k%N!<%I!J%/%i%9%?!K?t$,!$%i%$%sC10L$N4IM}$GL58z2=7?%W%m%H%3%k$rMQ$$$k=>Mh$NJ}<0$KHf$Y$FBgI}$KA}2C$9$k2DG=@-$,$"$k!%$3$NLdBj$r2r7h$9$k$?$a$K>>K\$i$,Ds0F$7$?$N$,!$5?;w%U%k%^%C%WJ}<0[18)] $G$"$k!%5?;w%U%k%^%C%WJ}<0$O!$COMA %^%7%s$J$I$GMQ$$$i$l$k3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0[9)] $N%G%#%l%/%H%j$r=LLs$7$?J}<0$H9M$($k$3$H$,$G$-$k!%$3$3$G$O!$$^$:!$3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$rDj5A$9$k!%

$3$NJ}<0$G$O!$%/%i%9%?!J%W%m%;%C%5!K$,MU$KAjEv$9$kLZ9=B$$N%M%C%H%o!<%/$rA[Dj$9$k!%$3$3$G!$LZ$N3F%N!<%I$,%Q%1%C%H$r6!5k$7$F!$F10l$N%Q%1%C%H$rJ#?t$N3,AX%9%?$K%^%k%A%-%c%9%H$9$k!%LZ9=B$$N%M%C%H%o!<

!y K\Mh$N5?;w%U%k%^%C%WJ}<0$O!$1s3V1BP1DL?.!$3,AX%^%k%A%-%c%9%H!$%m!<%+%k%^%k%A%-%c%9%H$rAH$_9g$o$;$?%G%#%l%/%H%jJ}<0$HDL?.J}<0$r$^$H$a$F$X$9$,!$K\O@J8$G$O3$N$&$A$N3,AX%^%k%A%-%c%9%HJ}<0$r8!F$$NBP>]$H$7$F$$$k!%




?^ **2** 3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0
Fig. 2 Hierarchical bit-map directory scheme.

$K$h$jI,MW$J%S%C%H?t$r:o8:$9$k!%

(2) 3F@a$K$*$$$F$=$N@a$GE,MQ$9$k%G%#%l%/%H%j$r 4IM}$7!$%Q%1%C%H$,$=$N@a$KE~C#$7$?$H$-$K%G%#%l %/%H%j$r0z$/!%$3$&$9$l$P!$$n$ ?JLZ$rMQ$$$?$H$-!$ 3F@a$K$*$$$F 1%G%#%l%/%H%j%(%s%H%j$K$D$-!$$n$ bit $N%S%C%H%^%C%W$r4IM}$9$l$P$h$$!%

A0<T$K$D$$$F!$JUMP-1 $G$O

- $"$k@a0J2<$O%V%m!<%I%-%c%9%H$H$9$k
- J#?t$N@a$GF10l$N%S%C%H%^%C%W$rMQ$$$k!%

$N$$$:$l$+!$$b$7$/$ON>J}$NAH9g$;$K$h$C$F!$3,AX$4

%/$G$"$k$+$i!$3F@a$K$*$$$FAw?.@h$NMU$,KvC<$K$H$K $n$ bit!J$n$ ?JLZ$G!K$N%S%C%H%^%C%W$r#1$D$@$1;}

;^$K$N$_%Q%1%C%H$rAw$l$P!$I,MW$J%/%i%9%?$K$N$D$Q$H$H$7!$0J2<$N 3 $D$N%G%#%l%/%H%j=LLsJ}<0$r:N

%1%C%H$,FO$/$3$H$K$J$k!%?^ **2** $K!$;0?JLZ$N:,$M$9$k!%%G%#%l%/%H%j%(%s%H%j$4$H$KI,MW$J bit ?t$O!$

**d** $G%^!<%/$5$l$?MU$K%Q%1%C%H$rAw$k>l9g$K$D$$$F3,AX$N $n$ ?JLZ$K$*$$$F $m \times n$ bit $H$J$k!%$5$i$K!$

$9!%$3$N$H$-!$3F@a$K 3bit $N%S%C%H%^%C%W$rM?$($k%S%C%H%^%C%W$O!$%Q%1%C%H$N%X%C%@Cf$K;}$D$3$H$,$G

$H$K$h$jAw?.@h$r40A4$K;XDj$G$-$k!%3,AX%S%C%H%^%C%W$N$G!$40A4$K%k!<%?Fb$N$_$G%^%k%A%-%c%9%H$,2D

%W%G%#%l%/%H%j$O!$%^%k%A%-%c%9%H$r9T$&$?$a$N%S%G$G$"$j!$30It$N%G%#%l%/%H%j$r;2>H$9$kI,MW$,$J$$!%

%H%^%C%W$G$"$j!$$3$l$K$h$C$FF10l$N7PO)$rF10l$N@a%SM K! 3F3,AX$4$H$K!$$=$N3,AX$N$9$Y$F$N@a$N=LLs

%1%C%H$,J#?t2sDL$k$3$H$,$J$/$J$k!% A0$N%S%C%H%^%C%W$NO@M}OB$r$H$j!$$=$N3,AX$N$9$Y

$J$*!$C1=c$JLZ9=B$$G$OLZ$N:,IU6a$N%H%i%R%C%/$F$N@a$GMQ$$$k!%

Bg$-$/$J$C$Fp'O)$H$J$C$F$7$^$&$?$a!$7k9gLV$O **LPRA** K! >>K\$i$,J88[18]$GDs0F$7$?J}K!$G$"$k!%

Tree $rFbJq$9$k$3$H$,K>$^$7$$!%$^$?!$%Q%1%C%H$O<%Q%1%C%H$OLZ$N:,$+$i6!5k$5$l$k$,!$85!9$O$$$:$l

:]$K$O$$$:$l$+$N%/%i%9%?$+$iAw?.$5$l$k$?$a!$Aw?.$NMU$KAjEv$9$k%/%i%9%?$+$iAw$i$l$?$b$N$G$"

85$N%/%i%9%?$+$iLZ$N:,$KMF0W$K%Q%1%C%H$rAw$k$3$H!%:,$+$i$3$NAw?.85$NMU$K;j$k%Q%9$r$=$NB>$N%Q

$,$G$-$kI,MW$,$"$k!%8e$K@bL@$9$k$h$&$K!$RDT $%9$H6hJL$7$F07$&!%%Q%1%C%H$O!$:,$+$i2<0L$N@a$K

$3$l$i$N@-<A$rK~$?$7$F$*$j!$3,AX%S%C%H%^%C%W%G%S%C%H%^%C%W$K=>$C$F=g$K%^%k%A%-%c%9%H$5$l$k$,!$

%l%/%H%jJ}<0$KE,$7$?9=B$$r;}$C$F$$$k$H$$$($k!%$"$k@a$GAw?.85$r4^$^$J$$$$%Q%9$N;^$K%Q%1%C%H$,Aw

**2.1** %G%#%l%/%H%jD9$N=LLs

$i$l$k$H!$$=$N;^$N2<$NItJ,$K$O%Q%1%C%H$,%V%m!<

3,AX%S%C%H%^%C%W%G%#%l%/%H%j$K$*$$$FI,MW$J bit %I%-%c%9%H$5$l$k!%$9$J$o$A!$:,$+$iAw?.85$NMU$X

?t$O!$$m$ 3,AX$N $n$ ?JLZ$K$*$$$F

$N%Q%9>e$N@a$K3F3,AX$N%S%C%H%^%C%W$,E,MQ$5$l!$

$$\sum_{k=1}^{m} n^k$$

$=$l0J30$N@a$G$O>e0L$N@a$+$i%Q%1%C%H$,Mh$l$P%V %m!<%I%-%c%9%H$r9T$&!%

J88[18]$G$O!$%Q%1%C%H$OAw?.85$NMU$+$iLZ$rAL$j$J

$GM?$($i$l$k!%D6JBNs7W;;5!$G$O!$%/%i%9%?!J%W%m%$$i%^%k%A%-%c%9%H$r9T$&$3$H$K$J$C$F$$$k$,!$$K\

%5!K?t$,Hs>o$KB?$$$?$a!$C1=c$K3,AX%S%C%H%^%C%W%G$*$$$FAj0c$O$J$$!%

%l%/%H%jJ}<0$rMQ$$$k$H!$%G%#%l%/%H%j$KI,MW$J**LARP** K! LPRA $HF1MM$K!$:,$+$iAw?.85$K;j$k%Q

%jNL$,KDBg$K$J$j!$<B8=$,:$Fq$G$"$k!%$b$A$m$s%U%9$r$=$NB>$N%Q%9$H6hJL$7$F07$&!%

%^%C%W$r$b$H$K3,AX%S%C%H%^%C%W$r:n@.$9$k$3$H$O LPRA $H$O5U$K!$$"$k@a$G

G=$G$"$k$,!$$3$l$K$O7k9gLV$N%H%]%m%8$K$h$C$F$OJ# Aw?.85$r4^$`;^

;($JA`:n$rI,MW$H$9$k$7!$%U%k%^%C%W$KI,MW$J%S%C% Aw?.85$r4^$^$J$$;^$N$&$A$N$$$:$l$+

?t$b$^$?Bg$-$/!$<B8=$O:$Fq$G$"$k!%0lJ}!$3,AX%S%N>J}$K%Q%1%C%H$,Aw$i$l$k$H!$Aw?.85$r4^$`;^$N

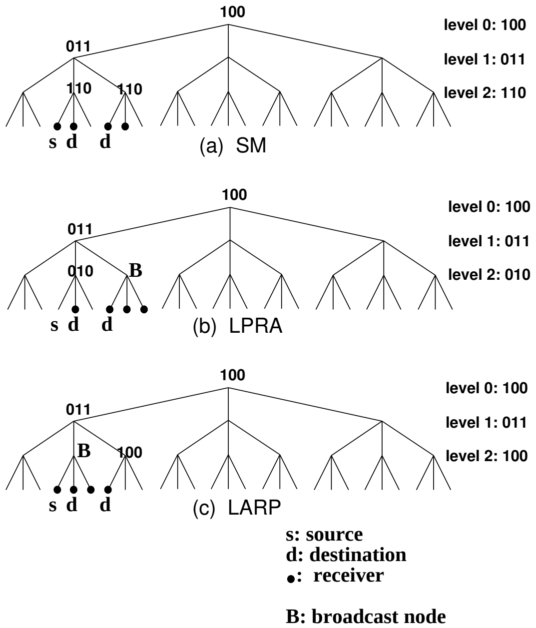
%H%^%C%W%G%#%l%/%H%j$rMQ$$$?:]$K!$3,AXh$K%G%#%2<$NItJ,A4BN$K%Q%1%C%H$,%V%m!<%I%-%c%9%H$5$l$k!%

%/%H%j$r0z$-D>$9$H!$>l9g$K$h$C$F$OBg$-$J;~4V$r$M$l0J30$N;^$G$O!$F10l3,AX$N$9$Y$F$N@a$G!$$=$l

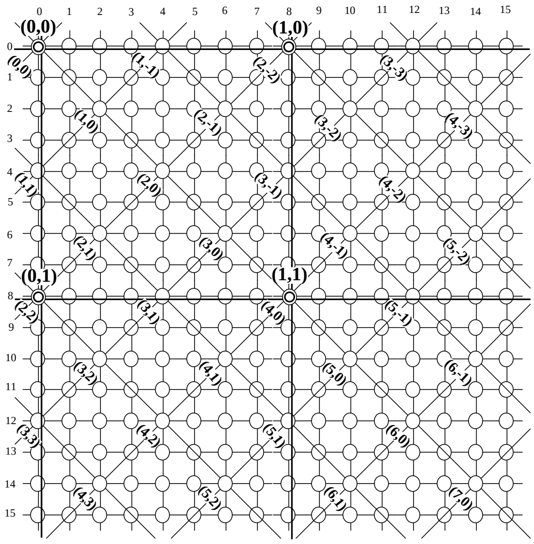
$9$k!%$=$3$G0J2<$K<($9%S%C%H?t$r=LLs$9$kJ}K!$,$M$N@a$N=LLsA0$N%S%C%H%^%C%W$NO@M}OB$rMQ$$$k!%

$($i$l$k!% ?^ **3** $K;0?JLZ$rMQ$$$?LN<0?^$r<($9!%$3$N?^$G **s** $,

(1) $$$/$D$+$N%/%i%9%?$r%0%k!<%W2=$7$F07$&$3$H$Aw?.85$N%/%i%9%?!$**d** $,K\Mh$NAw$j@h!$$●$,7k2LE*$K




?^ **3** %G%#%l%/%H%j=LLsJ}<0
Fig. 3 Directory reduction schemes.




?^ **4** RDT $N9=@.
Fig. 4 RDT (Recursive Diagonal Torus).

%Q%1%C%H$,Aw$jIU$1$i$l$k%/%i%9%?$G$"$k!%$7$?$,$C
$F!$**d** $N$J$$•$N?t$,>/$J$$$[$IL5BL$K%Q%1%C%H$r
$1<h$k%/%i%9%??t$,>/$J$$$3$H$K$J$k!%$3$N=LLs
$r:N$jF~$l$?3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0
Ls3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$H8F$V!%

## 3. 3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$N RDT >e$G$N<B8=

3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$G$OLZ9=B$
%a%C%;!<%8$rEAC#$9$k!%$7$+$7!$C1=c$J $n$ ?JLZ>e$K
AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$r<B8=$9$k$H!$
$NLdBjE@$,@8$8$k!%

(1) J#?t$N%N!<%I$,%^%k%A%-%c%9%H$r9T$J$C$?>l9g$N
%k!<%H$N6a$/$G%a%C%;!<%8$,=8Cf$9$k!%

(2) %D%j!<$NMU$K:8$+$i=g$KHV9f$r9_$C$?>l9g!$%
%j!<>e$N0LCV$K$h$C$F$O!$HV9f$,$H$J$j$"$C$?%N!
%I$KBP$7$F%Q%1%C%H$rAw$k$?$a$K$b!$%D%j!<A4BN$N
%k!<%H$^$GAL$C$?8e!$B?$/$N08@h$KBP$7$F%Q%1%C
$rJ|Aw$9$kI,MW$,@8$8$k!J?^ 2 $K$*$1$k X $+$i
$X$NE>Aw!K!%

$3$l$i$NLdBjE@$O!$J8%f$K=R$Y$i$l$F$$$k$h$&
$K!$<~0O%N!<%I$KBP$9$k6a@\%^%C%W!$1s3V$N 1 %N!<%I
$KBP$9$k 1 BP 1 ;XDj$rJ;MQ$9$k$3$H$K$h$j!$$"$kDxEY
$O2r7h$9$k$3$H$,$G$-$k!%

$7$+$7!$JUMP-1 $G$O 2 <!85%H!<%i%9$N3,AX9=B$
;}$D7k9gLV RDT!JRecursive Diagonal Torus!K[19)-21)]

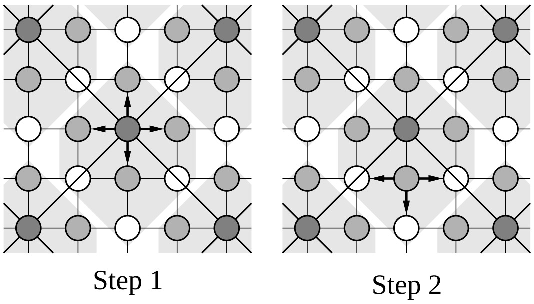
$rF3F~$9$k$3$H$K$h$j!$$3$l$i$NLdBj$NK\<AE*$J2r7h
$r?^$C$F$$$k!%

### 3.1 RDT $K$*$1$k%^%k%A%-%c%9%H$HLZ9=B$$N<B8=

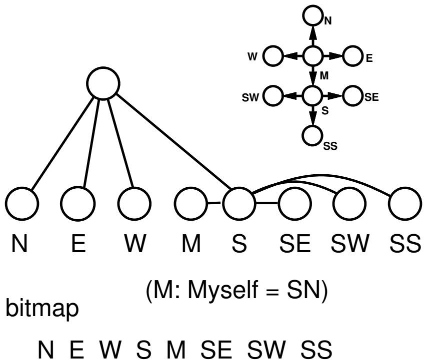
RDT $G$O!$01Dj$N%5%$%:$N 2 <!85%H!<%i%9!J%i%s
$/0%H!<%i%9!K>e$K0J2<$NJ}K!$G!$:F5"E*$K>e0L%H!<
%i%9$r9=@.$9$k!%$^$:!$%i%s%/ 0 %H!<%i%9$N$"$k%N!<
%I $(x, y)$ $KBP$7$F!$± 2 N%$l$?%N!<%I$KIU2C%j%s%/$r
2C$($k$H!$$3$NIU2C%j%s%/$K$h$j 45 EY79$$$?L\$NAF
$$%H!<%i%9$,9=@.$5$l$k!%$3$l$r%i%s%/ 1 %H!<%i%9
$H8F$V!%%i%s%/ 1 %H!<%i%9>e$KF1MM$N%"%k%4%j%:%`$G
IU2C$K>e0L%H!<%i%9$r9=@.$7!$%7%9%F%`$N5,LO$K$h$j
%H!<%i%9$,:n$l$J$/$J$C$?$i=*N;$9$k!%?^ **4** $K%i%s
%/ 2 $+$i 2 $^$G$N%H!<%i%9$r<($9!%$3$N?^$G$OFCDj$N
%N!<%I>e$K$N$_>e0L%H!<%i%9$r9=@.$7$F$$$k$,!$$9$Y
$F$N%N!<%I$KBP$7$F2DG=$J8B$j>e0L%H!<%i%9$r9=@.$9
$k$3$H$,$G$-$k!%$3$N9=@.$r40A4 RDT $H8F$V!%

40A4 RDT $O<!?t$,Bg$-$9$.$k$N$G!$<B:]$N RDT $O!$
%N!<%I$K$h$C$F>e0L%H!<%i%9$rJ,$1$F;}$D!%JUMP-1
$G$O3F%N!<%I$O!$%i%s%/ 0 %H!<%i%9$NB>$K%i%s%/ 1 $+
$i 4 $^$G$N$&$A!$#1$D$N%i%s%/$N%H!<%i%9$r;}$D9=@.
!JRDT!J2,4,1!K/$\alpha$!K$r$H$C$F$$$k!%$3$N9=@.$O!$1 %9
%F%C%W$N%k!<%F%#%s%0$G 1 $+$i 4 $^$G$N$9$Y$F$N>e0L
%H!<%i%9$,MxMQ2DG=$G$"$j!$65536 %N!<%I$KBP$7$F!$
<%I 8 $GD>7B 12 $r<B8=$9$k!%

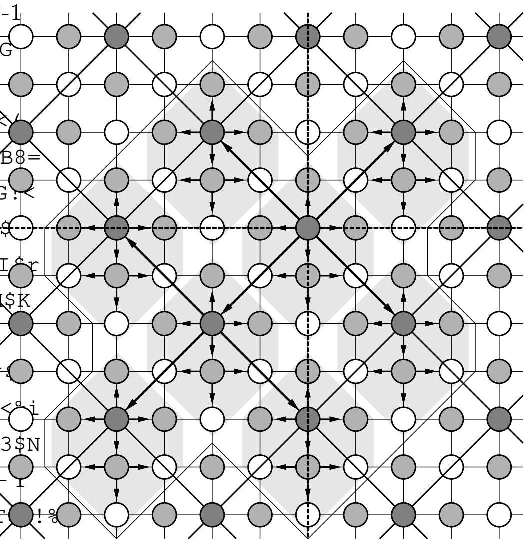
%k!<%F%#%s%0K!$O!$%Y%/%H%kJ,2r$rMxMQ$7$?4JC1$J
J}K!$G<B8=$G$-!$<o!9$NJBNs%"%k%4%j%:%`$,40A4 RDT
$rG0F,$K$*$$$F@_7W$9$k$3$H$,$G$-$k!%%V%m!<%I%-%c
%9%H!$%=!<%H!$%O%$%Q!<%-%e!<%V!$%D%j!<$N%(%_%e%l!<




?^ **5** 0l$D2<$N%i%s%/$N%N!<%I$X$N4pK\E>Aw%Q%?!<%s
Fig. 5 Multicast to the nodes of the lower rank torus.




?^ **6** 3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$GMQ$$$k 8 ?JLZ$H%S%C%H%^%C%W$H$NBP1~
Fig. 6 8-ary tree and corresponding bit-map for the hierarchical directory.



?^ **7** %^%k%A%-%c%9%H$N%F%j%H%j
Fig. 7 "Territory" of a multicast.

%7%g%s$,MF0W$K<B8=2DG=$G$"[20]!$k

3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$r<B8=$9$k$?$a$K$O!$RDT $N;}$D$D%j!<$N%(%_%e%l!<%7%g%s5!G=$rMxMQ$9$k!%0J2<!$FC$K;XDj$7$J$$>l9g!$40A4 RDT $rBP>]$K%"%k%4%j%:%`$N2r@b$r9T$&$,!$<B:]$K JUMP-1 $GMQ$$$k RDT!J2,4,1!K/$\alpha$MQ$K3HD%$9$k$3$H$OMF0W$G$"$k!%

RDT $K$h$k%D%j!<$N%(%_%e%l!<%7%g%s$O!$?^ **5** $K<($9559C7A$NNN0h$KBP$7$F$N%^%k%A%-%c%9%H$K$h$j<B8=$5$l$k!%$^$:!$%9%F%C%W 1 $G;MNYA4$F$N%N!<%I$K%G!<%?$rAw$k!%<!$K%9%F%C%W 2 $G 3 %N!<%I$,FCDjJ}8~$%G!<%?$rAw$k!%$3$NA`:n$O!$E>Aw$r3+;O$7$?%N!<%I$r4^$a$?5?;wE*$J 8 ?JLZ$r 2 %9%F%C%W$G9=@.$9$k$3$H$KAjEv$9$k!%

$"$k%i%s%/ $i$ %H!<%i%9$r;}$D$9$Y$F$N%N!<%I$K$*$$$F$3$N%Q%?!<%s$GE>Aw$r9T$&$H!$$3$N%i%s%/$N%H!<%i%9$r;}$D%N!<%I$9$Y$F$K$3$N%G!<%?$,Aw$i$l$k!%$3$N%Q%1%C%H$r<u$1<h$C$?%N!<%I$O$5$i$K!$%i%s%/ $i-1$ %H!<%i%9$KBP$7$FF1MM$JNN0h$K%^%k%A%-%c%9%H$r9T$&!%$3$N$3$H$K$h$j!$3F%i%s%/$KBP$7$F 8 ?JLZ$r7A@.$7$F$$$/$3$H$,$G$-$k!%

RDT $O>e0L%H!<%i%9$rJ#?t;}$D$?$a!$7k9gLVA4BN$H$7$F Fat-tree[5] $,7A@.$5$l$k!%$7$+$b<B:]$K JUMP-1 $GMQ$$$i$l$k RDT!J2,4,1!K/$\alpha$K$*$$$F3F%N!<%I$O 1$"$k%N!<%I$,?^ 6 $K<($9%Q%?!<%s$GE>Aw$9$k$H$-!$%9%F%C%W$N%k!<%F%#%s%0$G0lHVL\$NAF$$%H!<%i%9$I$N%i%s%/$+$i%^%k%A%-%c%9%H$9$k$+$K$h$C$F!$%Q%1%C%H$r%i%s%/!K$N%j%s%/$rMxMQ$9$k$3$H$,$G$-$k$N$G!$LZ%FO$/HO0O!J%F%j%H%j!K$,Dj$^$k!%?^ **7** $K$O%i%s%/Bg%i%s%/$N%k!<%H$KBP$7$FD>@\%Q%1%C%H$rE>Aw$9$k$3$H$,$G$-$N%F%j%H%j$,<($5$l$F$$$k!%%i%s%/$,Bg$-$$$[$I%F$k!%$3$N$?$a!$%^%k%A%-%c%9%H$N3+;O;~$KLZ$rAL$j1H%j$O9-$,$C$F$$$-!$%^%k%A%-%c%9%H$r9T$&%N!<%IMW$,$J$$!%F1MM$N<jK!$O!$%H!<%i%9/%a%C%7%e$K8B$i$J$$f?4$H$7$?IT5,B'$JF1?41_>u$K$J$k!%$:!$MM!9$J7ABV$N7k9gLVG$K$bF1MM$KE,MQ$G$-$k[11]$3$NJ}K!$K$O0J2<$KC1=c$J$D%j!<9=B$$d Fat Tree $KBP$7$F0J2<$NMxE@$,$"$k!%

**3.2** <B8=K!$N>\:Y

RDT!J2,4,1!K/$\alpha$K$*$1$k%^%k%A%-%c%9%H$O5?;wE*$J 8 ?JLZ$K$h$j9T$J$o$l$k$?$a!$3,AX%S%C%H%^%C%W$r<B8=$9$k$?$a$K$O!$3F3,AX$G 8 bit $N%S%C%H%^%C%W$,I,MW$H$J$k!%$3$3$G!$4pK\E>Aw%Q%?!<%s$KBP$7!$?^ **6** 

• >e0L%H!<%i%9$,J#?t8DB8:_$9$k$?$a!$C1=c$J$Dj!<9=B$$GLdBj$K$J$k>e0L%k!<%H$G$N:.;($O5/$3$i$:!$J#?t%N!<%I$G%^%k%A%-%c%9%H$,5/$-$F$b!$DL?.2Y$O<+A3$KJ,;6$5$l$k!%

- %F%j%H%j$O!$Aw?.%N!<%I$rCf?4$H$9$kF1?41_>u$K $J$j!$Aw?.%N!<%I$N0LCV$,JQ$o$k$H$=$l$K$H$b$J$$ O"B3E*$K0\F0$9$k!%$3$N$?$a!$C1=c$J%D%j!<$d Fat Tree $N$h$&$K!$;^$,0[$J$k$3$H$K$h$C$FHV9f$,6a@\ %N!<%I4V$N5wN%$,6KC<$KBg$-$/$J$kLdBj$O$*$-$J$$!%
- K\O@J8$G8!F$$9$kJ}<0$G$O!$1~Ez%Q%1%C%H$N<4K$8

;~$K%P%C%U%!$,$"$U$l$?>l9g$J$I$K MBP $,=hM}$9 9T$&$?$a!$$=$l$>$l$N%k!<%?$KBP$7$F MBP $H$a %b%j$,I,MW$K$J$k!% $3$N$?$a!$Fat Tree $J$I$N$$ 4V%N!<%I$,1i;;5!G=$r;}$?$J$$7k9gLV$G$O!$M>J,$J MBP $*$h$S%a%b%j$rI,MW$H$9$k!%$3$l$KBP$7 RDT $G$O!$LZ9=B$$NCf4V%N!<%I$,KvC<%N!<%I$KBP$7 $J$+$?$A$G3d$j?6$i$l$k!%

$7$+$7!$$3$NJ}K!$N7gE@$O!$%F%j%H%j$N7A>u$,1T B'$G$"$j%^%k%A%-%c%9%H$N$?$a$N%S%C%H%^%C%W$r mMQ $N$,Fq$7$$$3$H$G$"$k!%$3$N$?$a!$08@h%N!<%I$NA 0LCV$K$h$j$I$N bit $r%;%C%H$9$k$+$r<($9$F!<%V%k MQ0U$5$l$F$$$k!%%Z!<%8$r6&M-$9$k%N!<%I$,A} :]$K$O!$%N!<%I id $r%-!<$H$7$F$3$N%F!<%V%k$r0z $=$NCM$r$b$H$K%G%#%l%/%H%j$NFbMF$rJQ99$9$k!%$3 :]$KI,MW$J1i;;$O!$SM K!$G$OC1=c$JO@M}OB$G$"$j LPRA!$LARP K!$G$O$=$l$K2C$($F<c43$N>r7oH=CG$, I,MW$G$"$k!%

## 4. %G%#%l%/%H%j=LLsJ}<0$NBEEv@-

### 4.1 %Z!<%8$r6&M-$9$k%W%m%;%C%5?t

A0=R$N$h$&$K!$=>Mh$I$*$j%i%$%sC10L$K%G%#%l%/%H %j$r4IM}$7!$L58z2=7?%W%m%H%3%k$rMQ$$$k>l9g!$ 2=%a%C%;!<%8$N08@h$O!$1 $J$$$7 2 $,$[$H$s$I$G$"$H$NI>2A$,$G9T$J$o$l$F$*$j!$$h$j8=<BE*$JJ}K!$H 2>Dj$K4p$E$/:G6a$NI>2A$b$3$l$,N"IU$1$i$l$F$$ $k!%$=$3$G!$JUMP-1 $G9T$&$h$&$K%Z!<%8C10L$G4IM} $r9T$&>l9g$K%a%C%;!<%8$N08@h$,$I$N$h$&$K$J$k I>2A$7$?!%

?^ 8 $K!$6&M-%a%b%j$N$?$a$NJBNs%W%m%0%i%'=8 S PLASH[7] $K4^$^$l$k MP3D LdBj!J1024 N3;R!K$r 256 %W%m%;%C%5$G 1 H?I|<B9T$7$?:]$NL58z2=$H99?7%a %8$N08@h%W%m%;%C%5?t$NJ,I[!$$*$h$S water LdBj! ;R?t 64!"<B9T%9%F%C%W?t 1!"F=MA $r2r$/%*!<%@ $r 32 %W%m%;%C%5$G<B9T$7$?$NL58z2=%a%C%;!<%8$N 08@h%W%m%;%C%5?t$NJ,I[$r<($9!%$3$l$O!$%"%I%l%9 %l!<%9[14] $r4p$KJ,@O$7$?$b$N$G$"$k!%$3$3$G$O!$%-%c% %7%e%i%$%s$NBg$-$5$r 32 %P%$%H!$%Z!<%8$NBg$-$5$r

I=1 3FJ}<0$N%a%b%jI,MWNL

Table 1 Memory Requirement.

| N | FM | LD | HB | RHB |
|---|---|---|---|---|
| 4096 | 4096 | 72 | 4680 | 32 |
| 32768 | 32768 | 90 | 37448 | 40 |

4K%P%$%H$H$7$F!$%i%$%sC10L$H%Z!<%8C10L$G4IM}$7 $?>l9g$N08@h%W%m%;%C%5?t$NJ,I[$r$=$l$>$l<($7$F$$ $k!%$$$:$l$b2#<4$,08@h%W%m%;%C%5?t$rBP?t<4$G<($7 $F$b$N$G!$=D<4$,H/@8EY?t$G$"$k!% $3$l$i$N7k2L$+$i!$%i%$%sC10L$G%G%#%l%/%H%j$r4I M}$9$l$P!$FC$KL58z2=7?$G08@h%W%m%;%C%5?t$, 3 Dx <2<$K$J$k3NN($,$+$J$j9b$$$N$KBP$7!$%Z!<%8C10L $N4IM}$G$O08@h?t 4!A8 $K%T!<%/$,8+$i$l!$$=$l0J>e $N08@h$r;}$D>l9g$b$+$J$jB?$$$3$H$,J,$+$k!%99?77? mMQ$$$k>l9g$b$[$\F1MM$J798~$r;}$D$,!$%i%$%sC10L $G4IM}$7$?>l9g$N08@h?t$,$d$dA}$($k798~$K$"$k!%$7 $?$,$C$F!$%Z!<%8C10L$K4IM}$7!$99?77?$N%W%m%H%3%k $rMQ$$$k>l9g!$%^%k%A%-%c%9%H$,I,MW$K$J$k$3$H$,J, $+$k!%

### 4.2 I,MW$J%a%b%jNL

%N!<%I?t $N$ $,4096 $*$h$S 32768 $N%7%9%F%`$K$D $$$F!$%U%k%^%C%WJ}<0!JFM!K!$%j%_%F%C%I%G%#%l%/ %H%jJ}<0!JLD!K!$=LLs$rMQ$$$J$$$3,AX%S%C%H%^%C%W %G%#%l%/%H%jJ}<0!JHB!K!$=LLs3,AX%S%C%H%^%C%W%G%# %l%/%H%jJ}<0!JRHB!K$N$=$l$>$l$NJ}<0$,#1$D$N%( %s%H%j$r7A@.$9$k$?$a$KI,MW$J%a%b%jNL$rI= 1 $K<( $9!%$3$3$G!$%j%_%F%C%I%G%#%l%/%H%jJ}<0$O!$>/$J$/ $H$b$"$k%i%$%s$rJ?6QE*$K6&M-$9$k%W%m%;%C%5?t!J$9 $J$o$A%a%C%;!<%8$N08@h?t!K$KAjEv$9$k%]%$%s%?$r;} $D$;$k$N$,0lHLE*$G$"$k!%?^ 8 $K$h$k$H!$%Z!<%8C10L $N4IM}$r9T$J$C$?>l9g!$%V%m!<%I%-%c%9%H$r=|$$$?08 @h?t$NJ?6Q$r$H$k$H MP3D $OLs 6!"Water $OLs 5 $G $"$k!%$3$N$?$a!$$3$3$G$O%]%$%s%??t$r 6 $H$7$FI>2A $r9T$J$C$?!%

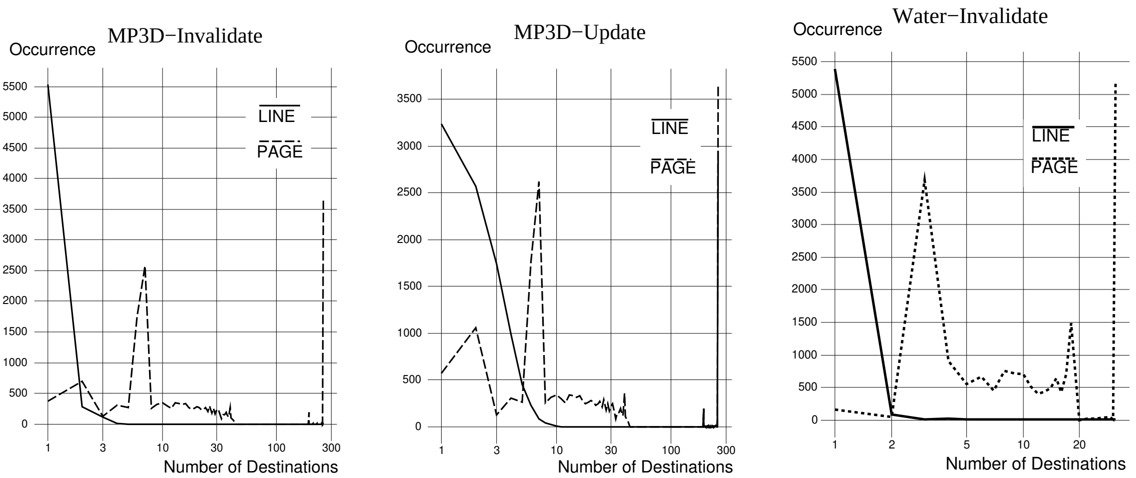
I= 1 $h$j!$=LLsJ}<0$O%j%_%F%C%I%G%#%l%/%H%jJ}<0 $H$[$\F1Ey$+!$$=$l$h$j$b>/$J$$%a%b%jNL$G%G%#%l%/ %H%j$r<BAu$G$-$k$3$H$,J,$+$k!%$J$*!$%a%b%jMW5aNL$K$D $$$F$O%A%'%$%s%I%G%#%l%/%H%j[3),8)] $b5M-Mx$G$"$k$,!$ 6 8NJ}K!$O!$$=$l$>$l$N%N!<%I$G%a%b%j%"%/%;%9$rI, MW$H$9$k$3$H$+$i%$%F%s%7%#$NE@$G$OITMx$G$"$k!%

### 4.3 <u$1$H$i$l$k%Q%1%C%H?t$NI>2A

=LLs3,AX%G%#%l%/%H%jJ}<0$O!$08@h0J30$N%N!<%I$K %7%e%i%$%s$NBg$-$5$r 32 %P%$%H!$%Z!<%8$NBg$-$5$r $7$F$bL5BL%Q%1%C%H$,Aw$i$l$F$7$^$&E@$KLdBj$,$" $k!%$=$3$G LPRA!$SM!$LARP $N 3 $D$K$D$$$F!$8 $N 4 >h$G$"$k 4096 $N%/%i%9%?$+$i9=@.$5$l$k RDT >e$G%Q%1%C%H$N08@h$N?t$HJ,I[$rJQ2=$5$;$?$H$-$K!$

---

!y water $G$O!$%H%l!<%9$,Bg$-$/$J$j$9$.$?$?$a!$250 K|L?Na<B 9T$7$?;~E@$G$H%l!<%9$N<}=8$rBG$A@Z$C$?



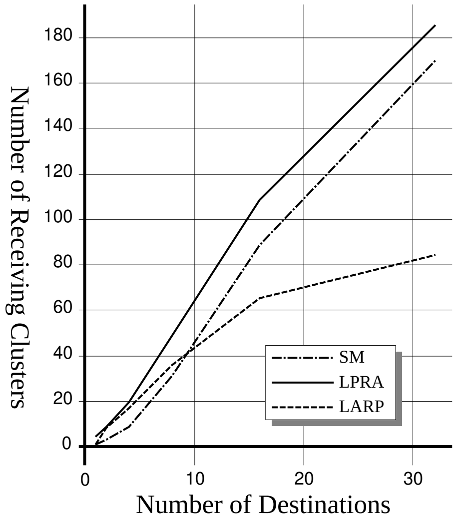

?^ 8 %a%C%;!<%808@h?t$NJ,I[
Fig. 8 Distribution of number of destinations.

#12s$N%^%k%A%-%c%9%H$"$?$j<B:]$K$$$/$D$N%/%i%9%
$K%Q%1%C%H$,<u$1$H$i$l$k$N$+$rD4$Y$?!%
K\Mh!$JUMP-1 $G$O%N!<%I$NCOM}E*$J5wN%$r9MN8$7
$?%9%1%8%e!<%j%s%0/%^%C%T%s%0$,A0Ds$H$J$C$F$$$k!%
$7$?$,$C$F!$I>2A$O!$<B:]$N%"%W%j%1!<%7%g%s%W%m%0%
%'$r8=<BE*$J%^%C%T%s%0"%k%4%j%:%'$K4p$E$$$F2L$
%T%s%0$7$?>u67$r2>Dj$7$F9T$J$o$J$1$l$P$J$i$J$$!%
$7$+$7!$$3$N$h$&$JI>2A$O!$%"%W%j%1!<%7%g%s$N0\?
%^%C%T%s%0"%k%4%j%:%'$NFC@-$,4XO"$9$k$?$a!$<o
$N>r7o$N2<$G?tB?$/$N%7%_%e%l!<%7%g%s$r9T$&I,MW$
$"$k!%8=:_$N$H$3$m!$B??t$N%N!<%I?t$r2>Dj$7$F9T$
$N%7%_%e%l!<%7%g%s$r9T$&4D6-$,$^$@@0$C$F$$$J$$$
$a!$:#2s$O!$08@h$rDj$a$i$l$?J,I[$K=>$&Mp?t$K$h$
7hDj$7!$$=$1$>$1$N>l9g$K$D$$$F Sun OS4.1.3 $N
='$NMp?tH/@8%i%$%V%i%j$rMQ$$$F 10000 2s$N;n9T$
$J$$!$J?6QCM$r$H$C$?!%
RDT $N%i%s%/ 0 %H!<%i%9>e$G08@h$NAw?.85$+$i
X J}8~!$Y J}8~$NAjBP0LCV$NJ,I[$,$=$1$>$1FHN)$N
!J%i%s%/ 0 %H!<%i%9>e$N 1 %j%s%/$rC10L$H$7$F!KI8$
JP:9 1 $N@55,J,I[$K=>$C$F$$$k>l9g$N%Q%1%C%H$
$1$H$k%/%i%9%??t$N%0%i%U$r?^ 9 $K<($9!%$3$N>l9
08@h?t$, 32 $N>l9g$G$b%Q%1%C%H$,Aw$i$l$k%/%i%9
?t$O 80!A180 DxEY$G$"$k!%$^$?!$08@h?t$,B?$$$H$
LARP $,M-Mx$G$"$k$3$H$,J,$+$k!%
?^ 10 $OI8='JP:9$r 5 $H$7$?$H$-$NF1MM$N%0%i%U
$"$k!%$3$N>l9g!$%Q%1%C%H$,Aw$i$l$k%/%i%9%??t$
$J$jB?$/$J$k!%$^$?!$08@h?t$,>/$J$$$H$-$K$O SM
08@h?t$,B?$$$H$-$K$O LARP $,M-Mx$G$"$k$3$H$,
$+$k!%$3$N798~$O!$B>$N%0%i%U$G$bG'$a$i$l!$$*$
$M08@h?t$, 10 DxEY0J2<$G$"$l$P SM $,!$$=$l0J>e$G

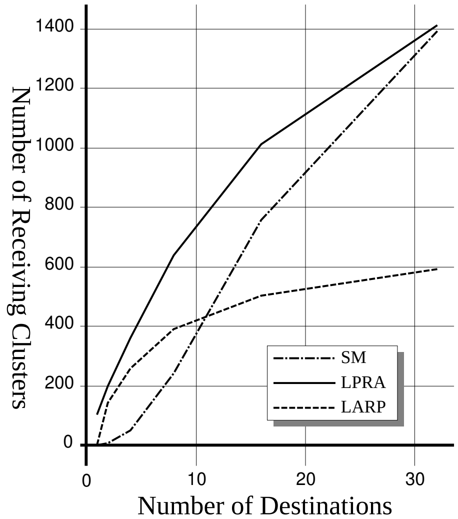
$9$1$P LARP $,M-Mx$G$"$k!%
A0=R$N$h$&$K!$%Z!<%8C10L$G$G%#%l%/%H%j$r4IM}$7
$?>l9g!$08@h?t 6 DxEY$K%T!<%/$,$"$k!%$=$3$G08@h?t
6!$K8GDj$7!$I8='JP:9$rJQ2=$5$;$F%Q%1%C%H$r<u$1
%H$k%/%i%9%??t$rD4$Y$?7k2L$r?^ 11 $K<($9!%$3$N7k
2L$b$j!$$D$M$K SM $,%Q%1%C%H$,Aw$i$l$k%/%i%9%??t
$,$G$b>/$J$$!$I8='JP:9$,Bg$-$/$J$C$F$b 380 DxEY$K
$H$I$^$C$F$$$k!%

4.4 %l%$%F%s%7%#$NI>2A

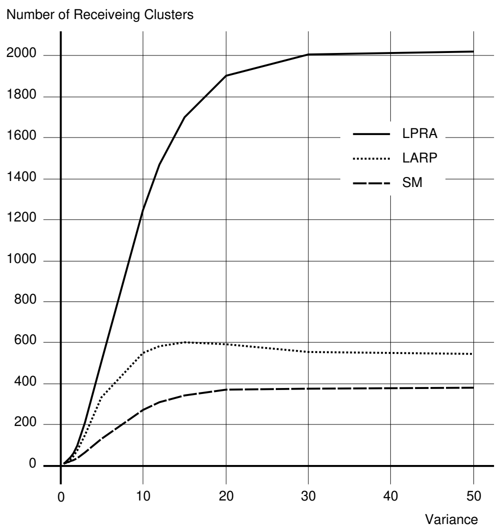
%j%_%F%C%I$G%#%l%/%H%j}<0$r$O$8$a$H$9$k=>Mh$N
J}<0$G$O08@h$N?t$@$1=g$K#1$D$:$D%Q%1%C%H$r MBP
$GAw$kI,MW$,$"$k!%$3$l$KBP$7!$=LLs3,AX%S%C%H%^%C
%W$G%#%l%/%H%j$G$O!$MBP $+$iAw$i$l$?%Q%1%C%H$O
$k!<%?Fb$G%^%k%A%-%c%9%H$5$l$J$,$i!$L\E*%N!<%I$K
Aw$i$l$k!%$7$?$,$C$F!$7k9gLV$,6u$$$?>uBV$G$"$l$P!$
=LLs3,AX%S%C%H%^%C%W$G%#%l%/%H%j$O!$=g$K#1$D$:$D
Aw$kJ}<0$KHf$Y$FL\E*%N!<%I$KE~Ce$9$k%l%$%F%s%7%#
$,Ce$GM-Mx$K$J$k!%
$7$+$70lJ}!$A0>O$NI>2A$K$h$k$H=LLs3,AX%S%C%H%^%C
%W$G%#%l%/%H%j}<0$O!$$+$J$j$N?t$NL5BL%Q%1%C%H$,
0$B$k$?$a!$$3$N%Q%1%C%H$,7k9gLV$d MBP $X$N%j%s
%/$N:.;($r0z$-5/$3$7!$%l%$%F%s%7%#$r0z$-1d$P$92D
G=@-$,$"$k!%
$=$3$G!$%7%_%e%l!<%7%g%s$K$h$j!$%Q%1%C%HE>Aw$N
6QH/@84V3V$rJQ2=$5$;!$L\E*%N!<%I$KE~Ce$9$k$^$G
$N%Q%1%C%H$NI>2A$r9T$J$C$?!%$9$Y$F$N%N!<
%I$,J?6QH/@84V3V$K=>$C$F%Q%1%C%H$rH/@8$9$k!%$3
$N$?$a!$H/@84V3V$,C;$1$l$P7k9gLV$O$h$j:.;($9$k$3
$H$K$J$k!%
%7%_%e%l!<%7%g%s$K$*$1$k%k!<%?$O!$<!@a$K=R$Y$k



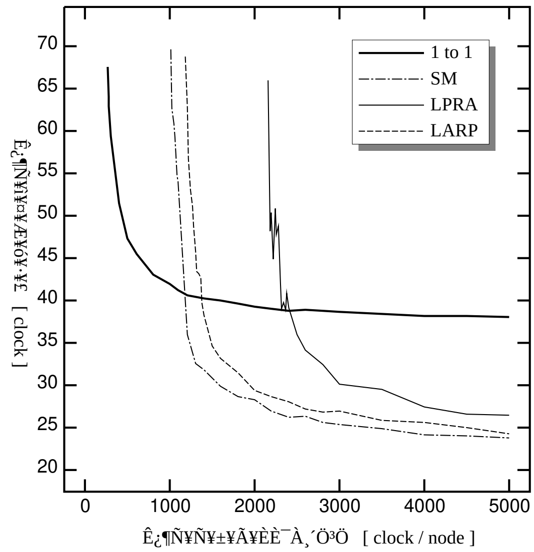

?^ **9** I8='JP:9 1 $GJ,I[$7$F$$$k>l9g
Fig. 9 Number of receiving nodes vs. number of destinations (SD=1).




?^ **10** I8='JP:9 5 $GJ,I[$7$F$$$k>l9g
Fig. 10 Number of receiving nodes vs. number of destinations (SD=5).




?^ **11** 08@h?t 6 $GI8='JP:9$rJQ2=$5$;$?>l9g
Fig. 11 Number of receiving clusters vs SD.

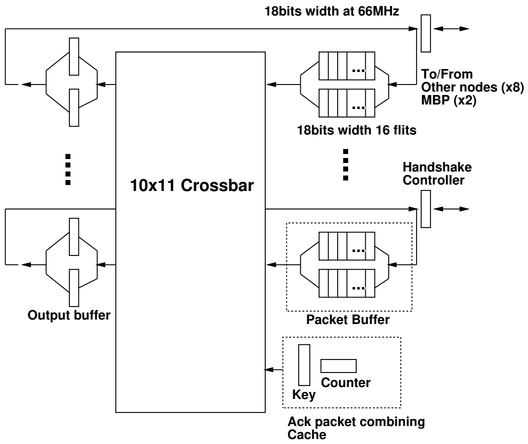



?^ **12** %Q%1%C%HE>Aw4V3V$H%l%$%F%s%7
Fig. 12 Latency vs. message transfer interval.

JUMP-1 MQ RDT %k!<%?$K$[$\Ci<B$K4p$E$$$FF0:n$9$k!%$?$@$7!$%Q%1%C%H$NDL2a;~4V$O 3 %/%m%C%/$H$7$?!%?^ 10 $K<($9$h$&$K!$%Q%1%C%H$,A}2C$9$k>u67!J08@h?t$r 6 MQ$H$7!$I8='JP:9 5!K$H$7$?!%$?$@$7!$%Q%1%C%H$N7_%e%l!<%?$N@)8B$K$h$j%N!<%I?t$O $16 \times 16 = 256$ %N!<%I$NAjBP0LCV$NI8='JP:9 5!K$H$7$?!%$?$@$7 $H$7$?!%$3$N7k2L$r?^ **12** $K<($9!%

3V$,C;$/$J$k$K$D$l!$$$$:$l$NJ}<0$G$b%l%$%F%s%7%#$,$Q-2=$9$k$,!$SM J}<0$H LARP J}<0$O7k9gLV$N@-$$$N8B3&$K6a$E$/$^$G!$1 BP 1 $K=g$KAw$kJ}<0$h$j$b%l%$%F%s%7%#$r<B8=$7$F$$$k!%$3$l$O!$=>Mh$N@5$7$/$G$O MBP $H%k!<%?4V$N%j%s%/$,%\%H%k%M%C%/$K$J$j!$$3$N%j%s%/$rBT$D%Q%1%C%H$,%k!<%?Fb$KD9;~4VBZN1$9$k$3$H$G!$L5BL%Q%1%C%H$,$"$k$N$HF1MMDxEY$N

?^ 12 $K$h$k$H!$=LLs%S%C%H%^%C%W%G%#%l%/%H%jJ}($,7k9gLV$K@8$8$k$?$a$H9M$($i$l$k!%<0$NJ?6Q%l%$%F%s%7%#$O!$1 BP 1 $K=g$KAw$k=>Mh$NJ}J>e$N%7%_%e%l!<%7%g%s$K$h$j!$=LLs3,AX%S%C%H%^%C<0$KHf$Y$FLs 40%2~A1$5$l$F$$$k!%%Q%1%C%H$NH/@8$W%G%#%l%/%H%jJ}<0$O!$L5BL%Q%1%C%H$K$h$k7k9gLV$N




?^ **13** %k!<%?%A%C%W$N4pK\9=@.
Fig. 13 The diagram of the RDT router chip.

:.;($r9MN8$7$F$b!$=>Mh$NJ}<0$KHf$Y%l%$%F%s%7%#$N E@$GM-Mx$G$"$k$3$H$,J,$+$k!%

## 5. JUMP-1 %k!<%?%A%C%W

8=:_!$K\O@J8$G8!F$$7$? LPRA, LARP, SM $9$Y$F $NJ}K!$r%5%]!<%H$7$? JUMP-1 %k!<%?%A%C%W$N3+H/ $,=*N;$7$F$$$k!%$3$N JUMP-1 %k!<%?%A%C%W$N9=@. $r?^ **13** $K<($9!%%i%s%/ 0 $N%j%s%/$K 4 K\!$>e0L%K% %/$N%j%s%/$K 4 K\!$MBP0!"MBP1 $K$=$l$>$l 1 K\$ $D%j%s%/$,I,MW$J$3$H$+$i!$A4BN$O 10 !_ 10 $N%/%m %P$,4pK\$K$J$j!$$3$l$K1~Ez%Q%1%C%H!JACK %Q%1 %H!K<}=85!9=$,2C$o$k!%E>Aw$N bit I}$O 1 %A%C%W$ $j3F%j%s%/$K$D$$$F 18bit $G$"$k!%JUMP-1 $G$O%k!< %?%A%C%W 2 8D$r%S%C%H%9%i%$%9$KMQ$$$k$3$H$K$h$j A4BN$G 36bit I}$r<B8=$9$k!%E>Aw<~GH?t$O%W%m%;%C%5 $KF14|$7$? 60MHz $G$"$j!$%7%9%F%`A4BN$,C10l$N%/ %m%C%/$GF0:n$9$k!%%Q%1%C%HDL2a;~4V$O%Q%1%C%H$N$ %$%W$K$h$j 5!A7 %/%m%C%/$G$"$k!%K\%k!<%?%A%C%W$ 07$&:GBg%i%s%/$, 3 $G!$4096 %N!<%I!J16384 %W%m%;% %5!K$N%7%9%F%`$KBP1~$9$k$3$H$,2DG=$G$"$k!%%i%s%/ 4V$N0\F0$K$O 5 %/%m%C%/!$%i%s%/ 3 $H%i%s%/ 0 0J3 $NBh 1 2sL\$N%^%k%A%-%c%9%H$K$O 7 %/%m%C%/!$$=$N $O 6 %/%m%C%/$rMW$9$k$?$a!$>WFM$,$J$1$l$P$I$N%N! %I$X$N%Q%1%C%H$bJ69 + %Q%1%C%HD9!K %/%m%C%/$G%^ %-%c%9%H$,=*N;$9$k!%%i%$%s$H%A%C%W$N%T%s$rM-8z$K MxMQ$9$k$?$a!$DL?.$O$9$Y$FAPJ}8~%i%$%s$K$h$j9T$o %A%C%W$OF|N)$N $0.5\mu m$ BiCMOS %2!<%H%"%l%$ HG22S125 $rMxMQ$7$?!%$3$N%2!<%H%"%l%$$O!$9b $G$"$k$&$(!$ECL F~=PNO$r;}$D$?$a!$MF0W$KE>Aw %$%s$rD>@\%I%i%$%V$9$k$3$H$,$G$-$k!%JUMP-1 $N Aw%Q%1%C%H$O 16flits!Jwords!K$G$"$j!$3flits $O 2 $D$N %A%C%W$K$D$$$F6&DL$NFbMF$N%X%C%@$H$J$k!%=LLsJ}<0 $GMQ$$$k%S%C%H%Y%/%H%k$O!$$3$N6&DL$N%X%C%@It$K3J G<$5$l$k!%E>AwJ}<0$O!$Wormhole %k!<%F%#%s%0$G$" $k$,!$3FF~NO$K$O%Q%1%C%H 1 8DJ,$r3JG<$9$k$3$H$N$G $-$k%P%C%U%!$r 2 %;%C%H;}$A!$$=$l$>$l$, 1 $D$N%A%c %M%k$r9=@.$9$k!%$3$N%A%c%M%k$r;H$$J,$1$k$3$H$K$h $j!$%G%C%I%m%C%/%U%j!<$J FIFO @-$NJ]>Z$5$l$?3,AX %^%k%A%-%c%9%H$r<B8=$9$k$3$H$,$G$-$k[20]!%K\O@J8$G =R$Y$?#3$D$N%^%k%A%-%c%9%HJ}K!$O%Q%1%C%H%X%C%@$N %S%C%H%Y%/%H%k$K=>$C$F!$%Q%1%C%HC10L$G@ZBX$(2DG= $G$"$k!%$5$i$K!$3F3,AX$G MBP $KN)$A$h$k$+$I$&$+ A*Br$9$k$3$H$,$G$-!$I,MW$K1~$8$F MBP $K$h$j$F!< %V%k$r0z$-D>$7$F%S%C%H%^%C%W$r9=@.$7D>$9$3$H$K$h $j!$=LLs$rMQ$$$J$$3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ} <0$r$b<B8=$9$k$3$H$,$G$-$k!%Am%2!<%H?t$OLs 90,000 %2!<%H$G!$%i%s%@%`It$OLs 50,000 %2!<%H!$%2!<%HMx MQN($OLs 63%$G$"$k!%

## 6. $*$o$j$K

D6JBNs7W;;5!JUMP-1 $N7k9gLV RDT $GMQ$$$i$l $k3,AX%S%C%H%^%C%W%G%#%l%/%H%jJ}<0$K$*$1$k%G%#%l %/%H%j=LLs$N$$$/$D$+$N<jK!$r<($7!$$3$l$i$N<jK!$G K\Mh$N08@h0J30$N%/%i%9%?$KAw$i$l$k%Q%1%C%H?t$r08 @h$r3NN(E*$KJ,I[$5$;$FB,Dj$7$?!$^$?!$%Z!<%8C10L $N%G%#%l%/%H%j4IM}$G$O!$08@h?t$, 6 DxEY0J>e$H$J$k >l9g$,B?$$$3$H$r%"%I%l%9%H%l!<%9$K4p$E$/JBNs%"%W %j%1!<%7%g%s$NI>2A7k2L$r$b$H$K<($7$?!%$3$l$i$N7k 2L$+$i!$%G%#%l%/%H%j=LLsK!$NM-8z@-$r$"$kDxEY<($9 $3$H$,$G$-$?!%

%5#2s$N7k2L$+$i$O!$08@h?t$,>/$J$$$H$-$K$O SM K! $,!$B?$$$H$-$K$O LARP J}$,M-Mx$H$J$C$F$$$k!%$$ $:$l$N%G%#%l%/%H%j=LLsK!$rMQ$$$k$+$O%Q%1%C%HCf$G %X%Dj$G$-$k$?$a!$%Z!<%8C10L$G;H$$J,$1$k$3$H$,$G$- $k!%<B:]$K$I$N$h$&$J>l9g$K$I$N<jK!$r;H$&$+$O!$%3 %s%Q%$%i$d OS $N=hM}$H$b4X78$7!$:#8e8!F$$9$kI,MW $,$"$k!%

$^$?!$$$$:$l$NJ}<0$G$b08@h?t$,B?$/$J$k$HITI,MW $J%Q%1%C%H?t$,B?$/$J$k!%$3$l$KBP=h$9$k<jK!$H$7$F!$ JUMP-1 $G$ODL>o%Q%1%C%H$K$O%"%/%N%l%C%8$,JV$5$l $k$3$H$rMxMQ$7!$ITI,MW$J%Q%1%C%H$r<u$1<h$C$?%/%i %9%?$+$i$O$=$N%"%I%l%9$X$N%Q%1%C%H$,ITI,MW$G$"$k $3$H$r%"%/%N%l%C%8%Q%1%C%H$KIU2C$7$FAw$k$3$H$K$h$j!$ %"%I%l%9$4$H$K!$LZ$N3F@a$NItJ,$G2<0L$N;^Cf$K$=$N %"%I%l%9$K$D$$$F$N%Q%1%C%H$rI,MW$H$7$F$$$k%/%i%9 %?$,$"$k$+$I$&$+$N>pJs$r MBP $K;}$?$;!$$3$l$r$b $H$KITI,MW$J%Q%1%C%H$r:o8:$9$k<jK!$r$H$k$3$H$b$G

$-$k!%$3$l$O@h$K<($7$?%G%#%l%/%H%j=LLs<jK!$N2 L\$G$"$k!$3F@a$K%G%#%l%/%H%j$N%S%C%H%^%C%W$r;}$?$;$k<jK!$KAjEv$9$k!%

$5$i$K!$0lK|%W%m%;%C%5$rD6$($k5,LO$GJ,;66&M-%a%b%j$r<B8=$9$k$?$a$NE>AwJ}<0$H$7$F$O%j%s%/$d%k!<%?$N8N>c$r2sHr$9$kJ}K!$r3NN)$9$k$3$H$,=EMW$G$"$k!%K\O@J8Cf$GDs0F$7$?<jK!$KBQ8N>c@-$rF3F~$9$k$?$a$K$O!$%^%k%A%-%c%9%H$r9T$&$?$a$NLZ9=B$<+BN$KBQ8N>c@-$r;}$?$;$kI,MW$,$"$k!%RDT $O!$J#?t$N>e0L3,AX%H!<%i%9$r;}$D$?$a!$7k9gLV<+BN$K$OBQ8N>c@-$,$"$j!$1 BP 1 E>AwMQ$K$O8N>c%k!<%?$d%j%s%/$r1*2s$9$k$3$H$N$G$-$k%k!<%F%#%s%0K!$,Ds0F$5$l$F$$$k[20]%k%A%-%c%9%HMQ$NLZ9=B$$b>e5-$N<jK!$r3HD%$7$FBQ8N>c@-$rF3F~$9$kJ}K!$,9M$($i$l$k$,!$8=>u$G$O%^%k%A%-%c%9%HMQ%S%C%H%^%C%W$r@8@.$9$kJ}K!$,L$8!F$$G$"$j!$:#8e$N2]Bj$G$"$k!%

K\9F$G=R$Y$?5!G=$O!$$9$Y$F%k!<%?%A%C%W$KAH$_9~$^$l$F$*$j!$:#8e$3$3$G<($7$?3<o$N%G%#%l%/%H%j=LLs<jK!$r<B:]$NJBNs%W%m%0%i%`$r8=<BE*$J%^%C%T%s%0%"%k%4%j%:%`$G%/%i%9%?$K3d$jEv$F$?>l9g$K4X$7$F8!F$$7$F$f$/M=Dj$G$"$k!%$5$i$K!$:#2s$N%l%$%F%s%7%$K4X$9$kI>2A$OBP>]%7%9%F%`$N%5%$%:$,>.$5$/!$$^$?3NN(%b%G%k$K4p$E$/$b$N$G==J,$J$b$N$H$O$$$($J$$!%$5$i$KBg$-$$%7%9%F%`$K4X$7!$<B:]$N%"%I%l%9%H%l!<%9$K4p$E$/%7%_%e%l!<%7%g%s$,I,MW$G$"$j!$:#8e$N2]Bj$G$"$k!%

<U<- $4;XF3$r$$$?$@$$$?El5~Bg3XM}3XIt$NJ?LZ0JGn;N!$>>K\>0Gn;N$r$O$8$a$H$9$k=EE@NN0h8&5fD6JBNs%W%m%8%'%/%H%a%s%P!<3F0L$K46<U$$$?$7$^$9!%

El5~9)2JBg3X>pJsDL?.9)3X2J$N;{_7BnLi;a!$>pJs9)3X2J$N9%B<8x0l;a!$J!EhBY?N;a!$8eF#=$;a!$?@EDOB?N;a!$>eED9-K~;a$K$O%7%_%e%l!<%7%g%s$K$46(NO$$$?$@$-46<U$7$^$9!%

%k!<%?%A%C%W$N@_7W$K$O%a%s%?!<%0%i%U%#%C%/%9<R$N%f%K%P!<%7%F%#%W%m%0%i%`$rMxMQ$7$?!%$^$?!$F1%A%C%W$N@=:n$K$OF|N)@=:n=j$*$h$SF|N)%^%$%3%s$N$46(NO$rD:$$$?!%?<$/46<U$$$?$7$^$9!%

K\8&5f$O!$0lItJ8It>J2J3X8&5fHq!J=EE@NN0h8&5f!J1!K2]BjHV9f 04235130 !VD6JBNs%O!<%I%&%'%"!&%"!<%-%F%/%A%c$N8&5f!W$K$K$h$k!%

## ;2 9M J8 8%

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(J?@. 7 G/ 9 7n 18 F|<uIU)
(J?@. 8 G/ 5 7n 14 F|:NO?)

@>B< 9n?.

1994 G/El5~9)2JBg3X9)3XIt>pJs9)3X2JB46H!%1996 G/7DXf5A=NBg3XBg3X1!M}9)3X8&5f2J7W;;5!2J3X@l96=$;N2]Dx=$N;!%8=:_!$F1Bg3X1!Gn;N2]Dx$K:_@RCf!%D6JBNs7W;;5! JUMP-1 MQ%k!<%?%A%C%W$N8&5f$K=>;v!%B>$K!$FPGA $rMQ$$$?650iMQ%^%$%/%m%W%m%;%C%5%7%9%F%`Ey$K6=L#$r;}$D!%

9)F# CN9(!J@52q0w!K

1991 G/7DXf5A=NBg3XBg3X1!M}9)3X8&5f2JGn;N2]DxC10L<hF@B`3X!%9)3XGn;N!%8=:_!$El5~9)2JBg3X>pJs9)3X2J@lG$9V;U!%JBNs=hM}7O%"!<%-%F%/%A%c!$N%;67O%7%_%e%l!<%7%g%s$NJBNs2=$N8&5f$K=>;v!%

@> 9(>O

1994 G/7DXf5A=NBg3XM}9)3XItEE5$9)3X2JB46H!%1996 G/F1Bg3XBg3X1!M}9)3X8&5f2J7W;;5!2J3X@l96=$;N2]Dx=$N;!%8=:_!$F1Bg3X1!Gn;N2]Dx$K:_@RCf!%D6JBNs7W;;5!8~$-%M%C%H%o!<%/MQ%k!<%?%A%C%W$N8&5f$K=>;v!%D6JBNs7W;;5!%M%C%H%o!<%/!$%k!<%?!$VLSI CAD Ey$K6=L#$r;}$D!%

ML 6rO%

1984 G/Cf9qKL5~G@6H5!3#2=3X1!EE5$2JB46H!%1996 G/7DXf5A=NBg3XBg3X1!M}9)3X8&5f2J7W;;5!2J3X@l96Gn;N2]Dx=$N;!%9)3XGn;N!%D6JBNs7W;;5!!&7k9gLV$N8&5f$K=>;v!%

E7Ln 1Q@2!J@52q0w!K

1981 G/7DXf5A=NBg3X9)3XItEE5$9)3X2JB46H!%1986 G/F1Bg3XBg3X1!M}9)3X8&5f2JGn;N2]Dx=$N;!%9)3XGn;N!%8=:_!$7DXf5A=NBg3XM}9)3XIt=u65<x!%JBNs7W;;5!$N8&5f$K=>;v!%