o 5-6: A E fic t MDS A ay o Sc to Acc at A D M at o

tao [1*] [2†] [1*] a M y G o[1*]
[1]S a a y a o ato y o Sca a o t a Sy t D at to o t Sc c E
S a a ao o ty S a a a
[2]D at to E ct ca o t E a o o at ty c o A SA
*{ ct o- y} c . t . c † o o A t o: c .

***Abstract*—W th th a g o/ th o ata sto ag , th a o h gh l ab l ty b co s c t cal la g ata c t s/ h RAID-5 s/ ly us . Ho/ th s a lu at c as s sha ly a t so usag , a thus co cu t s a lu s a ot a , th o RAID-5 s su fic t to o h gh l ab l ty. A solut o s to co t a x st g RAID-5 to a RAID-6 (a ty o "RAID l l g at o ") to tol at o co cu t s a lu s a asu co s, but x st g a oach s ol co l x co s o oc ss a h gh t a s o at o cost.**

o a ss th s chall g s, / o os a o l MDS co , call "Co 5-6", to co b a / cat a ty colu / th th o g al RAID-5 layout. Co 5-6 ot o ly acc l at s o l co s o o a RAID-5 to a RAID-6, but also o st at s s al o t al o t s o MDS co s. Ou ath at cal a alys s sho s that, co a to x st g MDS co s, Co 5-6 uc s / a t s, c as s th total I/O o at o s, a s s u th co s o oc ss by u to 80%, 48.5%, a 3.38×, s ct ly.

***Index Terms*—RAID; RAID L l M g at o ; MDS Co ; Ho zo tal Pa ty; D ago al Pa ty; R l ab l ty**

D

R at A ay o I o I t D RAID c a y A D-5 a co o o t o t o a c o c to y a ty o- a c a a a c o to a c , o a A D-5 co o t a ot t a t at o a ty c a ca y a o co a o c a t ct D E o DE 5 at t S cto E o SE tc y a t at t o o t at a ot c t at t a a A a a at A a a A a S cto E o at ASE c a a y a t a a o a y a , t fic t to t t t o t a 1% t o A 5 . So t a t o t t o a t o o to :

For a large data center based on RAID-5 arrays which has run a few years, how to maintain its high reliability and tolerate concurrent disk failures?

A t o a a oac a o o to c - co a o a c a t a ty o a ay 6 5 a o a to t t o to ***convert a RAID-5 to a RAID-6*** c a ty o ***RAID level migration*** a a t a ay to at o co c t a .

A E

A A ED A E A ES A S A A ED E A A ES A S A D A A SE E A ES ASE s AGE G S 5

	a	a	a	a	5 a
A	1.7%	8.1%	8.6%	5.8%	7.2%
A	0.7%	1.7%	4.3%	7.6%	6.8%
ASE	$1.1 * 10^{-9}$	$5.7 * 10^{-9}$	–	–	–
o ct	S a at : A 0.73%				
Ma a	t D ta : A 0.5% – 0.8%				

A D at o a ty ca t o to o ot a ty a ty o ata c t 5 . Ma y coo at o c a 5 DE S A a t c ot to y a to at c a a t A D at o . t o t co o o a A D-5 to a A D-6 ot o y o t oa a o A D t 5 t a o a a a y t a o ct o a ay A D at o a fica t ct o o A D co t o o t t a co a A D-6 6 5 t a t ay to o t a co o o a t A D-5 to a A D-6 :

1) ***RAID-5→RAID-0→RAID-6:*** D a t A D-5 to a A D- a t a t to a A D-6 . A a o a o t a A D-5 a t - at to o t a A D-6 y t ayo t o D co o , t a t A D-5→ A D- a o a t o a A D-5 a a at co o a t to o co t , o a a t a t A D- → A D-6 to to a t , t co o oc a o a t a ot t a t a a o o t a a a o a a t a t D to at .

2) ***RAID-5→RAID-4→RAID-6:*** D a t A D-5 to a A D- a t a t to a A D-6 . A a o o t a A D-5 a co t to o t a A D-6 y t ayo t o D co , t a t A D-5→ A D- a t a t a t ayo t o a A D-5 t-a y t c ot t o . t a a t a A D-5 co o t o a o a A D-6 o t a a t .

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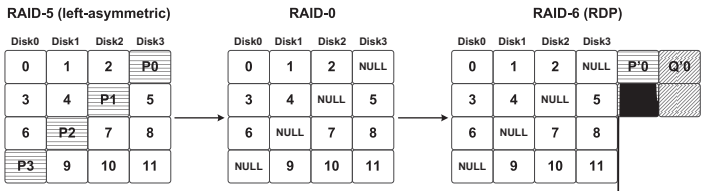


40% ca ac ty o ac o co o ,

1 4

a a t , A o a t t to
o co t , t tota t 4 1
c t a a o to a a ata oc a tt
to a A D- , ot a a a ty a a ty o a
a ay c a o o a cat o , o a ty ca
co o o a A D-5 to a A D-6 a ct o o t
a ay c a oc t ct o o
t co o oc 5 , t t co o co t
t oc ca ot acc y a y c t t
o co a co o a ty o t o a ,
o a t o t a o o a o
MDS co ca **Co 5-6** , t t t o a ayo t o
a A D-5 y y a a cat a ty co c
o t a t ct o a t a o at o t a A D-5
a a A D-6 , D o t o a
a ay o 5-6 a o t o o *p* *p* a
c o o 5-6 o t a y
o a A D-5 S ct o - ,
a t o o co t t o t o :

- o o a o - a A D-6 co o 5-6
to o o t o y t o ty o y ty ca MDS
co c a o t a to a fic cy a o t a -
co co co tat o a co ty t a o
fic cy o o ct o a co o t a

p + 1 *p* = 5 *n* = 6 .

3) ***RAID-5 – RAID-6:*** o t t A D-5 to a A D-6
ct y , A a o c y t
ayo t o - o 5 o o t
A D-6 a at y t t A D-5 , A o
a t o a A D-5 a a at a t to
a ot a o a a t - a o a t a t
- o a at t co o oc ,

a D a o a a ty co , A t - a o a a ty co ,

, , - o o *p* *p* = 5 *n* = 5 .

o t co o t o a o o ,
fi t t o a oac o t at A D

A E
S M S

a a t Sy o	D c t o
$m\ m'\ m''$	o a A D-5 o co o
n	o a A D-6 a t co o
v	o t a
p	a
w	o ca a a o o ac t a t a t
$i\ r$	o D
j	co D o D o t a o at o
B	tota o ata t oc a a ay y ca y a t co o to a oc
$C_{i,j}$	t at t it o a jt co
$f_1\ f_2$ $f_1 < f_2$	t o a o a co t D f_1 a f_2
$\sum$	o at o o t . . $\sum_{j=0}^{5} C_{i,j} = C_{i,0} \oplus C_{i,1} \oplus \cdots \oplus C_{i,5}$
$\langle\ \rangle$	o a a t t c . . $\langle i \rangle_p = i \mod p$
T_e	acc t o a a t t to a t

A D-5 a a A D-6 to t c a ayo t,

- ct o a co o a o t a o o 5-6 c o co c t A D a- t o t a A D-5 a a A D-6,
- co ct a o a t tat a a y o a o co o t o a o t MDS co a o t at o 5-6 ac co o fic cy co a to ot t a oac .

t o t a co t a o o : S ct o c t at o o t A D-6 co a t ot at o o o o , o 5-6 c ta S ct o , o co o a o t a c S ct o , S ct o t a t tat a a y o t co o co t a o a o a oac , a y co c o o S ct o .

, E A ED A D M A

t ct o c t a co a o ot at o , o ac tat t c o a t y o t a a ,

A. Existing Erasure Codes

A D-6 tat o a a o a o a co- t c o o a ca to t o cat o : MDS co a o -MDS co , **M**a **D** ta c **S** a a **MDS** co A D-6 ca t to t o- c a : o o ta co a t ca co , o o ta co c -So o o co a c y -So o o co 6 E E DD co D co a - ot co 5 at o co t o co tc, t ca co co ta - o 6 - o 5 - o yc c co - o 55 D co 56 a o 5 , y ca y o -MDS co o D co EA E co o co ME co 5 y a co 6 at - o a o -M 5 , t co A D-6 a y a co c

A E
M A S AM G D E E MDS DES E S M A
A D-5 A A D-6

MDS o	S t o a c	o o o ty	o o E fic cy
E E DD	o		o
D	M		o
- o		M	M
- o		M	M
- o			o
D	M	M	M
o 5-6		o	

a S - o 6 - o S A co o co G D o oca co t ct o o 5 a t a -MDS co oca y a a o 6 SD co ca to at co c t a o t o o a a c o co t y t ,

B. Motivation

A D-5 y t a y to ay a ca ata c t a ty a c a , t t a at o c a a y a t a y a o a a o a , S co a a ay ca co c t a a ot co o , o t c t ca to to at t a a ata c t , o o t o to A D-6, o o a ata c t t co t y to a A D-6 o t c atc , A a t at ay to co t a t A D-5 a to a y t to a A D-6 o t y a t to o t a ty a t o c t o t a ct t a a a ty o t y t ,

A a a o a co o o a A D-5 to a A D-6 t co o fic cy c y:

t o a c c cat t co t to o a ata t oc co o co ty t tota o a co o c c y t co o ty

, , A D-5→ A D- → A D-6 o A D-5→ A D-6 a t c t t ayo t o A D-5 a A D-6, Acco to a t co c a co o co ty c ot at to o o a o co to ac fic t A D at o ,

, DE 5-6

o 5-6 acc at o t a o at o o a A D-5 to a A D-6 y a o co to to a o a a t , o 5-6 a o t o o p p a ,

A. Data/Parity Layout and Encoding of Code 5-6

o 5-6 co o o a $p-1$ - o -p-co at t a tota o $p-1 * p$ t , a t ty o t t at : ***data elements horizontal parity elements*** a ***diagonal parity elements***, $C_{i,j}$ $0 \le i \le p-1$ $0 \le j \le p-$ ot t tat t it o a t jt co , a t co co $p-1$ o a o a a ty, E c t a t co t a at a

t t a a o a a ty t a t $p-$ ata t to co t o t ata t C_{i,f_1} fi t o o ta t o o t a o a a ty t, A t a o a a ty t o r a t y $C_{r,p-1}$ a o E at o a,

$$r \quad \langle i \quad f_1 - 4 \rangle_p$$

a o E at o t o t ata t ca co,

$$C_{i,f_1} \quad C_{r,p-1} \oplus \sum_{j=0}^{p-2} C_{\langle i+f_1-j \rangle_p, j} \qquad 5$$
$$j \ / \ f_1 \quad and \quad j \ / \ \langle i \quad f_1 \quad \rangle_p$$

Algo th 1: co t ct o A o t o o 5-6

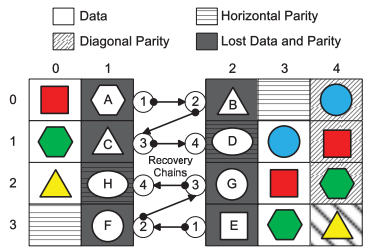
St 1: t y t o a co : f_1 a f_2 $f_1 < f_2$.
St 2: Sta t co t ct o oc a co t o t ata a a ty t .
s tch $0 \le f_1 < f_2 \le p-2$ **o**
  cas *I:* $f_2 = p-2$ *(diagonal parity column is lost)*
    St 2-IA: co t o t ata a o o ta a ty t co f_1 a o E at o a
    St 2-IB: co t o t a o a a ty t co f_2 a o E at o .
  al s
  cas *II:* $f_2 \neq p-2$ *(diagonal parity column is saved)*
    St 2-IIA: o t t o tat o t $C_{f_2-f_1-1,f_1}$ a $C_{p-1-f_2+f_1,f_2}$ o t co y c a a o E at o 5.
    St 2-IIB: co t o t ata t t t o co y c a .
    o cas s sta t sy ch ou ously:
    cas *starting point is* $C_{f_2-f_1-1,f_1}$ **at** o t t t o t co o f_2 t co y c a a o E at o a co t t t o t ata t co o f_1 t co y c a a o E at o 5.
    u t l *at the endpoint of the recovery chain* (C_{p-2-f_2,f_2}).
    cas *starting point is* $C_{p-1-f_2+f_1,f_2}$ **at** o t t t o t t co o f_2 t co y c a a o E at o a co t t t o t ata t co o f_1 t co y c a a o E at o 5.
    u t l *at the endpoint of the recovery chain* (C_{p-2-f_1,f_1}).
  al s
al s

a o E at o to 5 ca a y co t o t t o a a , t o a o a co f_1 a co f_2 $0 \le f_1 < f_2 \le p-$ a o o a o co t ct o a o t o o 5-6 a o A o t , A co t ct o ca A o t co y t o c a o 5 .

E. Properties of Code 5-6

1) ***Optimal Storage Efficiency:*** o t oo o o 5-6 co ct o 5-6 t a y a MDS co c a o t a to a fic cy 5 .

2) ***Optimal Encoding/Decoding Computational Complexity:*** o t co a co at o E at o to 5 o o 5-6 ac at o a $p-$ o at o , o at a $*p-1$ a t a t $*p-1*p-$ o at o o a c $\frac{2*(p-1)*(p-3)}{(p-1)*(p-2)}$ $\frac{2p-6}{p-2}$



, 5 , co t ct o y t o co y c a A t at o a a co 1 a 2 : t t y t t o tat o t o co y c a : ata t A a E . S co co t ct ata t acco to t co o co y c a t t y ac t o t a ty t D a H , o to co ata a a ty t a : o A→B→C→D t ot E→F→G→H .

o at o ata t , t ot a to co a y t $p-$ ca c at o o ta , S o n_d t o ata t a n_e t tota o t ac t , t o t at t at t o t a co a co co tat o a co - ty a $\frac{3*n_d-n_e}{n_d}$ $\frac{3*n_d-n_e}{n_e-n_d}$ ct y , o o 5-6 n_d $p-$ $* p-1$ a n_e $p* p-1$, t o t a co tat o a co ty a $\frac{3*n_d-n_e}{n_d}$ $\frac{2p-6}{p-2}$ $\frac{3*n_d-n_e}{n_e-n_d}$ $p-$ c a t a a t t a o co a co at o , o o 5-6 a o t a co co co tat o a co ty .

3) ***Optimal Single Write Performance (also known as "Optimal Update Complexity"):*** o t co t ct o o o 5-6 ac ata t ta a t to t at o o t o a o y t o a ty t , o a t o o ata t o 5-6 o y ca t o o fica t o o a ty t c a o to o t a 55 .

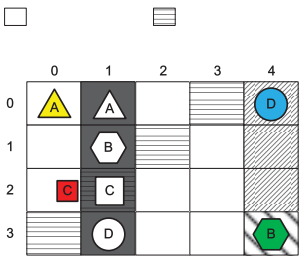
4) ***High Reliability on Single Disk Recovery:*** a *et al.* 5 o o a y co y a oac a o D co c ot o o ta a a o a a t to co a , t ca co t a c t co y t to 1 . 0% c ca a y MDS co to o a ty 56 .

a oac ca a o a o 5-6 to ac a ty , o a a o 6 co 1 a ot a t to a o co y , ca o t c a $C_{2,2}$ a a to co t o a t t a t , y t a oac p o 5-6 c to % a o at o a , 1 a y ty ca co y a oac t to co c c a t co y t M a t c a t a ty o t a ay ,

E E S A G MS

A. Bidirectional Conversions between RAID-5 and RAID-6

ct o a co o t a A D-5 a a A D-6 a ty o A D at o a t a t o a o 5-6 a o to a A D-5 a a cat a ty to t a A D-6 o o t a t co o a A D-6 to to A D-5 , A t o o 5-6 o t


0
1
2
3
4
A
A
D
B
C
C
D
B

a A D-5 o a y to a A D-6 t t y ac fic t to a fic cy c ca c at y

$$\frac{m * m-1}{m * m \quad 1 \quad v} \quad \frac{n-1 * n-}{n-1 * n \quad v} < \frac{n-}{n} \qquad 6$$

A o m a n 4 t to a fic cy $\frac{(4-1)*(4-2)}{(4-1)^4+1}$ /1 c a t a MDS co A D-6 $\frac{n-2}{n}$ $\frac{4-2}{4}$ 1/ a a y t ct o a o o t at t a ty o to a fic cy a a a o .

E S A A S S

t ct o o a a y to o t at t ct o o o 5-6 to co t a A D-5 to A D-6

A. Methodology

ct t co o a oac c S ct o a co a o A D-6 co :

1) RAID-5→RAID-4→RAID-6 a RAID-5→RAID-4→RAID-6: t o a oac a ta o a co a c oo E E DD D a - o 55 o co a o .

2) RAID-5→RAID-6: a oac a o at o o t t ca co a c - o 5 - o D 56 a o 5-6 o co a o . o to a o a o co a o ct t o ayo t o A D-5 a t o o o co a o , o a - o a c a a t- a o a a ty ayo t c ta o co o o t-a y t c A D-5 to A D-6 t t ca t at a o a A D-5 o $p-1$ co t to a A D-6 y a , A t o co o a o t a o o 5-6 ca a o t o y co o o oa a co o a a y , o co a o A D-5→ A D- → A D-6 D-6 ot to co t a A D-5 o to a A D-6 o 6 a A D- D , S a y A D-5→ A D-6 o 5-6 5 a t co o o a A D-5 o to a A D-6 o 5 ct y o 5-6 , t co o oc t a t ty o o at o o a t : t a a t to at o a t to a at a t , Acco to a o ty o o at o o a t t o o t c to a at t fic cy o a o co o .

1) Local Parity Ratio: at o t t o a a ty oc o a A D-5 a t to t co o oc a t tota o ata oc , o a a y a t co o to a ata oc a a t tota o ata oc B .

2) Global Parity Migration Ratio: at o t t o at a ty oc a t tota o ata oc .

3) Parity Update Ratio: at o t t o y at a ty oc a t tota o ata oc .

4) Next Stack Ratio: at o t t t a ac a t tota ca ac ty o ac .

5) Computation Cost: ota o o at o t co o oc .

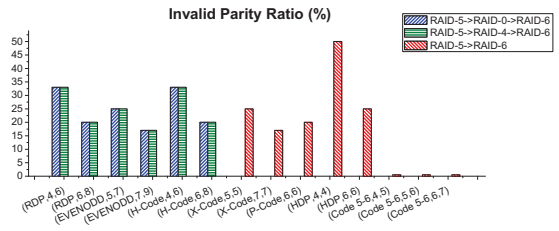
6) Write I/Os: ota o t o at o t co o oc .

) Total I/Os: ota o o at o t co o oc .

) Conversion : co t o t co o oc , a t a t o a a o t t to a ata a ty t a o t co tat o t c c a co a to t t , o a o a co o A D-5→ A D-6 o 5-6 5 t a a ty at o o a ty at o o - fication at o a ac at o a o , a ty at o at o $\frac{4}{3*4}$ 1/ a t t a $\frac{B}{3}$ t t tota a B $\frac{B}{3}$ $\frac{4B}{3}$, co tat o co t $\frac{B}{12} * *4$ $\frac{2B}{3}$ a t co o t $\frac{B*T_e}{3}$.

B. Numerical Results

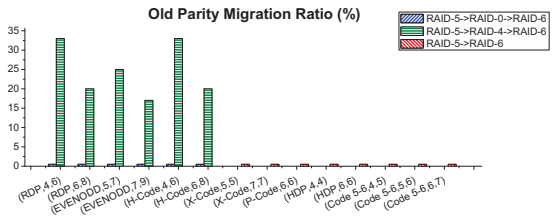
A t o o ct o t tat o t o o A D-6 a o o to a oa a a c o o MDS co , t t oa a a c o t c t t cat a ty a t at y o y a t , ot t o t oa a a c o t , t a o a ca o ca - a ty t o t fica t a ct o a ay c a y co t to A D-6 y ac fic oo o a c o o a A D-5 , t o oa a a c o t a a to t o t oa a a c o t a t ct o o y t t o co o t , t ca c at t a a ty at o o a ty - at o at o a ty at o at o a t a ac at o a o a oac a o to , t c a t at ct co o o a A D-5 to a A D-6 a t a t at o a o t t c c a t o t co t o o a ty at o c a y to 100.0% a a ty at o c a y to 0.0% .



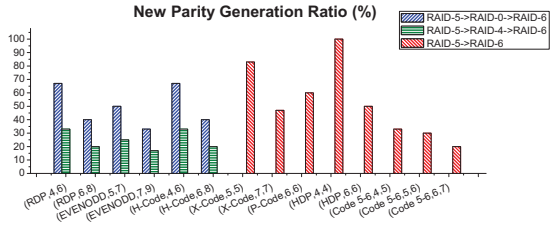
, , o a o o a a ty at o t co o a oac a o A D-6 co .

S co a o a oac co a t co - tat o co t t o at o tota o o at o a co at o t a o to 6 , t

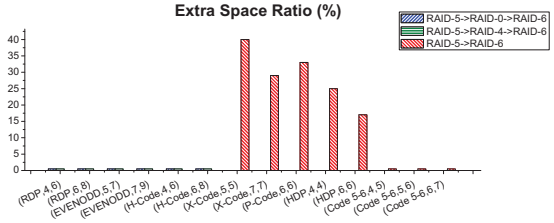
, , t a ac o A D-5→ A D-6 - o a o c .



. . o a o o o a ty at o at o t co o a oac a o A D-6 co .

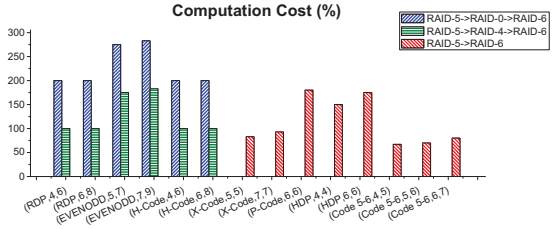


. . o a o o a ty at o at o t co o a oac a o A D-6 co .



. . o a o o t a ac at o t co o a oac a o A D-6 co .

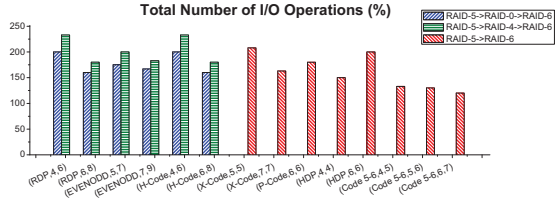
c a o t co tat o co t to o a ty c a t t a tota c ca o t o o a t , co o t a o c ca o a a , E a co a a o o ca o 5-6 c ct y co t a A D-5 to A D-6 a t o t co tat o co t t t a tota , t c a t co tat o co t t a tota y to .4% 0.0% 4 . % ct y .



. . o a o o co tat o co t t co o a oac a o co B o at o o a to 100% .

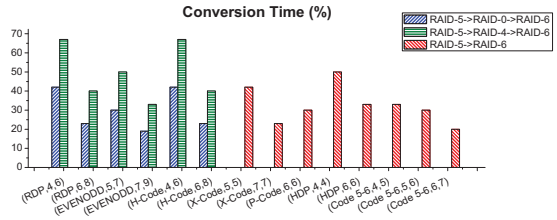
ca c at t co o t t o c a o

. . o a o o t t co o a oac a o A D-6 co B o at o o a to 100% .



. 5. o a o o tota t co o a oac a o A D-6 co B o at o o a to 100% .

t oa a a c o t a t o t oa a a c o t , t a o 6 a , a a o co t t t co o a oac t a a o n a o a , ot c t at o 5-6 ca acc at t co o oc co a to ot co y to 1 0% .



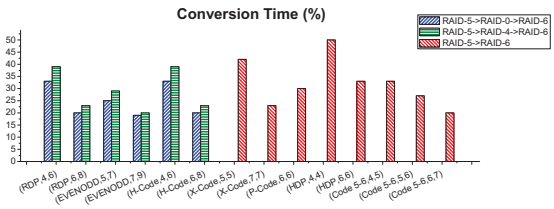
. 6. o a o o co o t t co o a oac - y a o A D-6 co t t o t oa a a c o t $B * T_e$ o a to 100% .

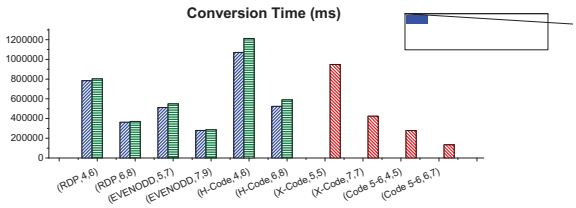
a y ca c at t to a fic cy t a o o m a A D-5 c c S ct o - , to a fic cy o a ty ca A D-6 t m 1 $\frac{m+1-2}{m+1}$ $\frac{m-1}{m+1}$. Acco to E at o

A E

S EED U DE 5-6 US G D E E S M A A D-5 A A D-6 E E DES US G E ES A A ES E MS E S ME

n	D	E E DD	- o	- o	- o	D
$n = 5$	–	–	–	1.27×	–	–
$n = 6$	1.40×	–	1.40×	–	1.00×	1.15×
$n = 7$	–	1.50×	–	1.15×	–	–
$n = 5$	–	–	–	1.27×	–	–
$n = 6$	1.22×	–	1.22×	–	1.11×	1.22×
$n = 7$	–	1.25×	–	1.15×	–	–





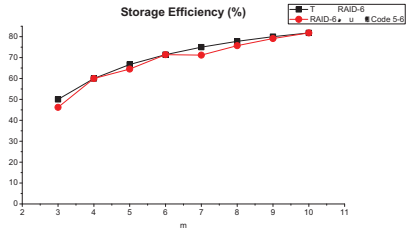
, , o a o o co , o t t co , o a - oac y a o A D-6 co t oa a a c o t $B * T_e$ o a to 100% ,

A E

S EED U DE 5-6 US G D E E S M A A D-5 A A D-6 E E DES US G E ES A A ES E MS E S ME

p	D	E E DD	- o	- o
$p = 5$	2.24×	1.48×	3.00×	2.71×
$p = 7$	2.40×	1.83×	3.38×	2.76×

6 t to a fic cy o a A D-6 o 5-6- t m 1 $\frac{m*(m-1)}{m*(m+1)+v}$ $\frac{(n-1)*(n-2)}{(n-1)*n+v}$, t a o a ot c t at t a a , o ct o t to a fic cy t a . % ,



, , Sto a fic cy co a o t ty ca A D-6 a A D-6 o 5-6 ,

C. Simulation Results

t ct o t at o t o co o t y a o co o a oac , t at t y t t c t ac o t at o y a o co c c a o t t o at at ca a a y a 5 , oc t to o ty ca y t t o 56 a t tota o ata oc B t to 6 o , D a t ato to a at t co o t c t o a t to a à t t t ac , t a o a a , t c a t at t t a a o p o 5- 6 a t co o t y to .0% , p co a o to o 5-6 ac , .

D. Analysis

o a o t co a to ot co o 5-6 a at a a ta o co o o a A D-5 to a A D-6 a ty o A D at o , a a a o

A EDGEME S

t a a o y o o t t co t , o a t a y o o y t at o a o a o a o , 5 5 t at o a at a Sc c o - at o o a o 6 6 6 5 o 6 o 6 o 6 o , 6 5 a o , 6 t o a o a a Sc o a a o at a c a - ty 5 S t Sc t fic o at o Act o S - SM o , 5 5 t S a a at a Sc c o at o o , a t Sc t fic a c o t - t a Sc o a , o o at a t a y o o y t S , S G at S - 6 a S - , A y o o fi a co c o o co a - t o t at a a t o o t a t o a o ot c a y ct t o t a c ,

E E E ES

A a t c c , A a t c Sto a Ma a : G , tt : o oa a a t c co _ a a t c _ t o a _ a a _ _ _ _ - -a , , a a a a a t a , A a a y o a t t cto o , *Proc. of the SIGMETRICS'07* ,

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D c , Ma a : A o t E 6 a E 6 o to - , tt : o t , co o t oc to a A D E 6 G M c at , t 6 ,

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D , att o t a , A ca o a t A ay o , D A D , *Proc. of the SIGMOD'88* ,

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