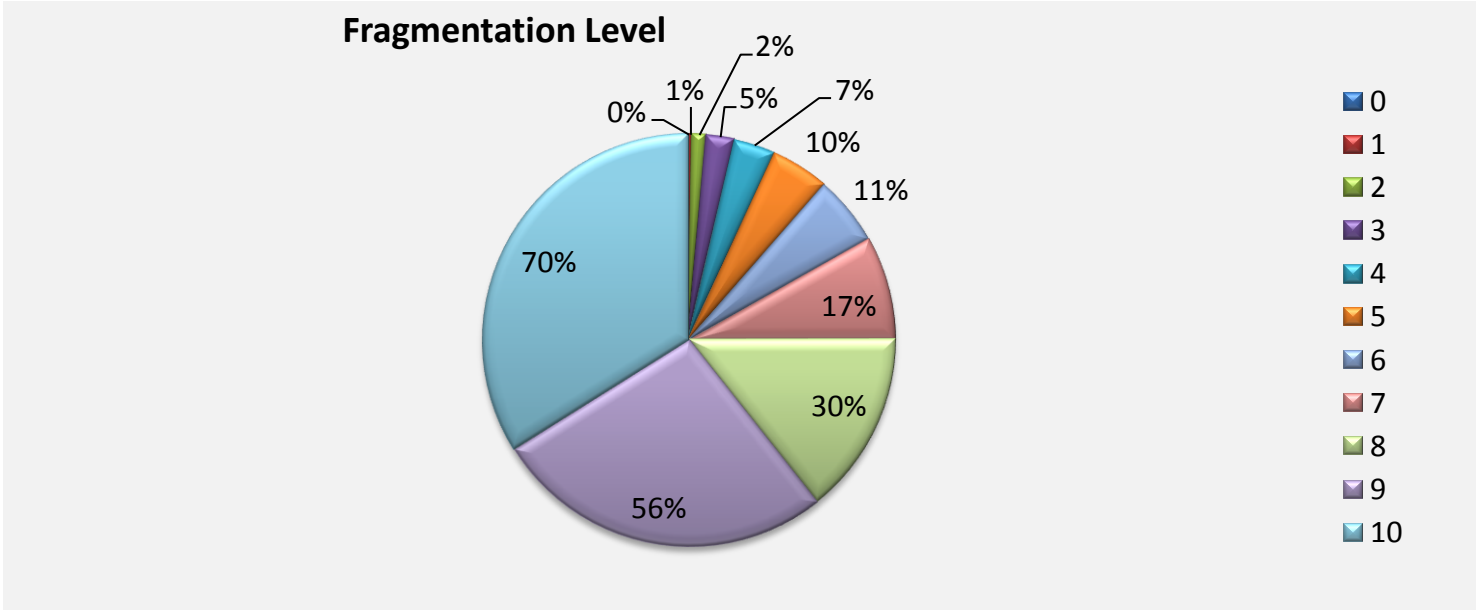
Linux Memory Fragmentation: Observation and Analysis on Smart Phones



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INTRODUCTION

- **What is Memory Fragmentation ?**

When a Linux device has been running continuously over a time without reboot and keeps allocating and de-allocating pages, the pages become fragmented. The bigger contiguous free pages become zero and free pages are only available in many smaller pages which are not contiguous. Thus even if we have lots of free memory in smaller units, the page allocation in kernel may fail.

This typical problem is called "External Memory Fragmentation" here after referred to as memory fragmentation.

INTRODUCTION

- **Effect of Memory Fragmentation :**
  - **Memory Fragmentation can cause a system to lose its ability to launch new process.**
  - **Memory fragmentation becomes more of an issue in embedded devices and Linux mobiles.**
    - **DRAM + Flash , Swapless system**
  - **Memory fragmentation can become more critical with high multimedia and graphics activities which requires contiguous higher-order pages.**

MEASURING FRAGMENTATION LEVEL

- It is important to measure fragmentation level across each zones and for each higher-order allocation in kernel.
- We believe by measuring fragmentation level during page allocation we can control higher-order allocation failure in kernel.
- We developed kernel utility to measure fragmentation level during runtime without enabling memory COMPACTION.

MEASURING FRAGMENTATION LEVEL

- **Formula to measure fragmentation level in percentage :**

$$FragLevel(\%) = \frac{TotalFreePages - \sum_{i=j}^{N} (2^i . k_i)}{TotalFreePages} X100$$

TotalFreePages	=	**Total number of free pages in each Node**
N	=	**MAX_ORDER - 1 ➔ The highest order of allocation**
j	=	**the desired order requested**
i	=	**page order ➔ 0 to N**
Ki	=	**Number of free pages in ith order block**

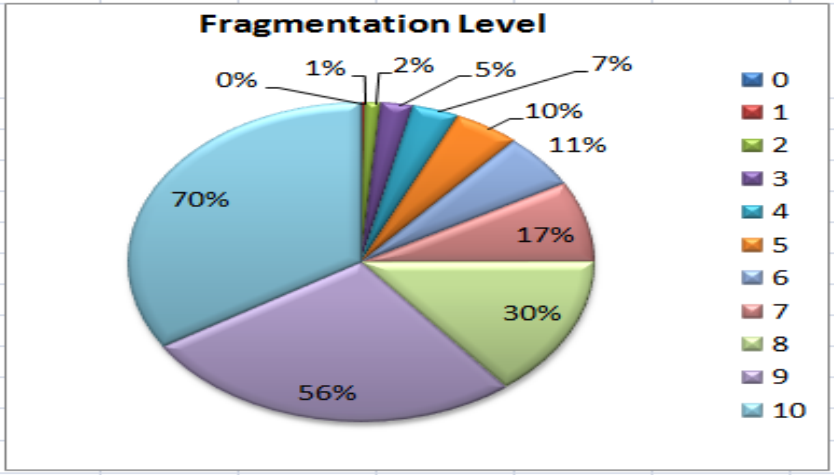
(The above formula derived from Mel Gorman's paper : "***Measuring the Impact of the Linux Memory Manager***")

MEASURING FRAGMENTATION LEVEL

- **SAMPLE OUTPUT : cat /proc/fraglevelinfo**

Fragmentation Level Measurement (cat /proc/fraglevelinfo)

Page Order (i)	Page Block (k)	Free Pages	Movable Pages	Reclaimable Pages	Fragmentation Level [%]
0	1	38	36	1	0%
1	2	59	55	2	1%
2	4	40	32	1	2%
3	8	19	16	0	5%
4	16	12	10	1	7%
5	32	4	2	1	10%
6	64	6	4	1	11%
7	128	7	4	0	17%
8	256	7	0	1	30%
9	512	2	1	0	56%
10	1024	2	2	0	70%
TOTAL		6932	3954	377	19%



$$FragLevel(\%) = \frac{TotalFreePages - \sum_{i=0}^{N}(2^i k_i)}{TotalFreePages} X100$$

Example:

Lets say a NORMAL zone looks like this at some point of time

	2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
Node 0, zone Normal	3	20	104	13	13	1	1	1	0	0	0

Now lets apply our formula to measure fragmentation level for order 2^5.

Here , TotalFreePages = (3x1 + 20x2 + 104x4 + 13x8 + 13x16 + 1x32 + 1x64 + 1x127) = 994

Therefore;
% Fragmentation =
(994 - [(2^5)*1 + (2^6)*1 + (2^7)*1 + (2^8)*0 + (2^9)*0 + (2^10)*0]) * 100) / 994

% Fragmentation = (994 - [32 + 64 + 128]) / 994 = ((994 – 224) * 100) / 994

%Fragmentation = (770 * 100) / 994 = 77.46 % ➔ 77 % (round off)

MEMORY FRAGMENTATION ANALYSIS

- We developed a sample kernel module and test utility to perform higher-order allocation and doing memory fragmentation analysis before and after the allocation.
- Test utility developed and tested for (K32, K36)
- Test Utility will be shared on LTP after further improvements.

JUST AFTER PHONE BOOT-UP (Linux Kernel 2.6.36)

```
/opt/home/root # cat /proc/fraglevelinfo
Node:0, Zone:Normal
Order    FreePages  MovablePages  ReclaimablePages  Fragmentation[%]
   0            2             0                 1               0%
   1            2             1                 1               0%
   2            5             1                 2               0%
   3            3             1                 2               0%
   4            4             1                 2               0%
   5            2             1                 1               0%
   6            6             1                 0               0%
   7            5             1                 1               0%
   8            1             0                 0               1%
   9            1             0                 1               1%
  10          102           101                 0               1%
TotalFreePages: 106414
TotalMovablePages: 103678
TotalReclaimablePages: 731
Overall Fragmentation: 0%

Node:0, Zone:HighMem
Order    FreePages  MovablePages  ReclaimablePages  Fragmentation[%]
   0           15             5                 0               0%
   1           15             2                 0               0%
   2           11             2                 0               0%
   3           10             5                 0               0%
   4           10             6                 0               0%
   5           11             6                 0               0%
   6            4             2                 0               1%
   7            8             5                 0               1%
   8            1             1                 0               3%
   9            1             0                 0               3%
  10           55            54                 0               4%
TotalFreePages: 59049
TotalMovablePages: 56665
TotalReclaimablePages: 0
Overall Fragmentation: 1%
```

```
/opt/home/root # cat /proc/buddyinfo
Node 0, zone   Normal      2      2      5      3      4      2      6      5      1      1    102
Node 0, zone  HighMem     15     15     11     10     10     11      4      8      1      1     55
```

AFTER RUNNING VARIOUS APPLICATIONS (Browser, WiFi Video Share, Camera, Voice Recorder, eBooks, Few Games) for ½ an Hour and then killing All)

```
/opt/pintu # cat /proc/fraglevelinfo
Node:0, Zone:Normal
Order    FreePages  MovablePages  ReclaimablePages  Fragmentation[%]
   0        1139           800                 1               0%
   1         795           540                 7               1%
   2         500           345                 2               3%
   3         315           229                 1               5%
   4         237           168                 0               8%
   5         114            70                 1              13%
   6          67            26                 1              17%
   7          25            15                 1              23%
   8          35            10                 1              26%
   9          16             9                 0              37%
  10          42            36                 0              47%
TotalFreePages: 82333
TotalMovablePages: 57636
TotalReclaimablePages: 511
Overall Fragmentation: 16%

Node:0, Zone:HighMem
Order    FreePages  MovablePages  ReclaimablePages  Fragmentation[%]
   0        2281          1994                 0               0%
   1        1382          1140                 0               9%
   2         861           781                 0              21%
   3         474           430                 0              36%
   4         226           193                 0              52%
   5         106            85                 0              67%
   6          38            26                 0              82%
   7           8             6                 0              92%
   8           3             0                 0              96%
   9           0             0                 0             100%
  10           0             0                 0             100%
TotalFreePages: 23513
TotalMovablePages: 19078
TotalReclaimablePages: 0
Overall Fragmentation: 59%
```

```
/opt/pintu # cat /proc/buddyinfo
Node 0, zone   Normal   1139    795    500    315    237    114     67     25     35     16     42
Node 0, zone  HighMem   2250   1382    861    474    226    106     38      8      3      0      0
```

ALLOCATION SUCCESS CASE – (Kernel 2.6.32)

```
/opt/pintu # ls -l /dev/pinchar
crw-------    1 root     root       10,  49 Jan 12 13:21 /dev/pinchar
```

```
/opt/pintu # ./app_pinchar.bin
```

	2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
Node 0, zone DMA	3	1	1	1	0	0	0	1	0	0	0
Node 1, zone DMA	197	129	0	0	0	0	0	0	0	0	0
Node 2, zone DMA	30	12	14	4	5	8	6	4	2	1	27

Enter the page order(in power of 2) :	16	2^4 order block	16 x 4K = 64K bytes
Enter the number of such block :	5		

State After The Allocation Request Is Successful

	2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
Node 0, zone DMA	3	1	1	1	0	0	0	1	0	0	0
Node 1, zone DMA	169	143	1	0	0	0	0	0	0	0	0
Node 2, zone DMA	19	12	12	5	2	7	6	4	2	1	27

Explanation :

5 of 2^4 order blocks were requested. These request could only be satisfied by Node 2, Thus Node 2 were selected for allocation. But in Node 2 also, out of 5 (2^4) blocks only 3 could be allocated. Then the other 2 were allocated by splitting the 2^5 order blocks.

$5 \times 2^4 = [3 \times 2^4 + (1 \times 2^5)] = [3 \times 2^4 + (1 \times 2 \times 2^4)] = [5 \times 2^4]$

ALLOCATION FAILURE CASE – (Kernel 2.6.32)

Buddy State Before Allocation

	2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
Node 0, zone DMA	1	0	0	0	1	0	2	0	0	0	0
Node 1, zone DMA	247	181	15	1	1	2	0	9	10	8	11
Node 2, zone DMA	19	19	11	3	6	3	4	2	2	2	29

Enter the page order(in power of 2) :	1024	**2^10 order block**	**1024 x 4K = 4096K bytes**
Enter the number of such block :	50	**(this is the highest order)**	

ERROR : ioctl - PINCHAR_ALLOC - Failed, after block num = 48 !!!

Explanation : **As you can see the allocation request of 1024 x 50 pages is failed after 47 such allocation. But still there were enough free pages available in lower order.**

Buddy State After Allocation FAILED And Other Allocation Freed

	2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
Node 0, zone DMA	1	0	18	9	0	0	0	0	0	0	0
Node 1, zone DMA	88	77	36	25	25	43	23	19	18	11	20
Node 2, zone DMA	18	14	10	4	5	2	3	3	2	2	29

Explanation : **The interesting think to note here is that after requested allocation was failed, kernel tried to arrange that many blocks in desired order so that next similar request can be succeeded.**

Observations

- __alloc_pages_nodemask : This is the heart of all memory allocation in kernel.
- We measure fragmentation level for each higher order here.
- Track higher-order allocation during high fragmentation. Anything above PAGE_ALLOC_COSTLY_ORDER(==3) is considered higher-order allocation in kernel and becomes critical.

Observations

- Direct reclaim does some progress but still could not return any pages during first run.
- Similarly direct compact is helpful but only if pages are movable.
- According to our observation: direct_reclaim leaves many pages MOVABLE.
- Thus we think first direct_reclaim and then direct_compact may be more useful under certain conditions. We will see these results in next slides.
- According to our experiment, a minimum of 2 sec delay is required after direct_reclaim to succeed subsequent allocation.

Experiments Results

- **We performed some experiments with higher-order allocation and got some results.**
- **We found that whenever we run any application "Xorg" perform 4 or 8 order allocation.**
- **The browser always requires order-4 allocation.**

/opt/pintu # ps ax | grep browser
7159 ? Ssl 0:03 /opt/apps/com.samsung.browser/bin/browser

[3830.215613] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 1168, NAME = Xorg> !!!
[3830.227243] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 8, Fragmentation Level = 29%
[3830.235645] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 1168, NAME = Xorg> !!!
[3830.244575] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 4, Fragmentation Level = 13%
(Around 10 times)

[3831.355884] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 7159, NAME = browser> !!!
[3831.364649] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 4, Fragmentation Level = 13%
[3831.373484] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 7159, NAME = browser> !!!
[3831.383134] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 4, Fragmentation Level = 13%
(Around 26 times)

RESULT #1 - (With Kernel 2.6.32)

	2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
Node 0, zone DMA	685	104	1	1	0	0	0	1	0	0	0
Node 1, zone DMA	33	19	31	18	9	1	1	0	0	0	0
Node 2, zone DMA	11	50	9	5	5	3	2	1	0	0	0

Enter the page order(in power of 2) :	1024	**2^10 order block**	**1024 x 4K = 4096K bytes**
Enter the number of such block :	10	**(this is the highest order)**	

```
[24768.550017] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 2289, NAME = app_pinchar.bin> !!!
[24768.559578] [HIGHERORDER_DEBUG] : ZONE : DMA, NODE : 0, ORDER = 10, Fragmentation Level = 100%
[24768.568020] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 2289, NAME = app_pinchar.bin> !!!
[24768.578686] [HIGHERORDER_DEBUG] : ZONE : DMA, NODE : 1, ORDER = 10, Fragmentation Level = 100%
[24768.587251] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 2289, NAME = app_pinchar.bin> !!!
[24768.597919] [HIGHERORDER_DEBUG] : ZONE : DMA, NODE : 2, ORDER = 10, Fragmentation Level = 100%
[24768.606486] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask : Allocation going via - slowpath !!!
[24768.615141] app_pinchar.bin: page allocation failure. order:10, mode:0x4020
← ---------- Wait for 2 seconds and retry allocation ---------- →
[24770.669441] [HIGHERORDER_DEBUG] : Trying - Final time !!!!!!!!!!
[24770.686688] <PINCHAR> : PINCHAR_ALLOCATE - Success(index = 0) !
```

Explanation : As you can see here, due to 100% fragmentation, page allocation request was failing, even after direct reclaim (slow path). But after a delay and retrying allocation request again, all subsequent allocation were successful.
This delay indicates something needs to be done after direct reclaim. Maybe wait till lazy buddy allocator arranges free pages in the subsequent free areas.

RESULT #2 – (Kernel 2.6.36) [Without COMPACTION]

Initial Fragmentation Level

```
/opt/pintu # cat /proc/fraglevelinfo ; cat /proc/buddyinfo
Node:0, Zone:Normal
Order     FreePages       MovablePages     ReclaimablePages         Fragmentation[%]
  0         271                25                0                        0%
  1         171                 5                0                        2%
  2         143                 1                1                        4%
  3         100                 1               18                        9%
  4         154                 1               61                       15%
  5          79                 2               27                       33%
  6          26                 1                6                       53%
  7           7                 3                3                       65%
  8          10                 0                0                       72%
  9           0                 0                0                       92%
 10           1                 0                0                       92%
TotalFreePages: 13117
TotalMovablePages: 575
TotalReclaimablePages: 2756
Overall Fragmentation: 39%

Node:0, Zone:HighMem
Order     FreePages       MovablePages     ReclaimablePages         Fragmentation[%]
  0        6850               6837                0                        0%
  1        8826               8803                0                       26%
  2         261                255                0                       95%
  3           9                  1                0                       99%
  4           5                  5                0                       99%
  5           0                  0                0                      100%
  6           0                  0                0                      100%
  7           0                  0                0                      100%
  8           0                  0                0                      100%
  9           0                  0                0                      100%
 10           0                  0                0                      100%
TotalFreePages: 25698
TotalMovablePages: 25551
TotalReclaimablePages: 0
Overall Fragmentation: 83%

Node 0, zone   Normal    271    171    143    100    154     79     26      7     10      0      1
Node 0, zone  HighMem   6850   8826    261      9      5      0      0      0      0      0      0
```

After Higher order allocation request

 # ./app_pinchar.bin 1024 25

[17949.789934] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 27713, NAME = app_pinchar.bin> !!!
[17949.801633] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 10, Fragmentation Level = 92%
[17949.811073] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask : Allocation going via - slowpath !!!
[17949.831793] [HIGHERORDER_DEBUG] : did_some_progress = 151
[17949.844090] [HIGHERORDER_DEBUG] : NO pages.....even after direct reclaim
[17949.859104] app_pinchar.bin: page allocation failure. order:10, mode:0x40d0
←---------- Wait for 2 seconds and retry allocation ----------→
[17951.879156] [HIGHERORDER_DEBUG] : Trying - Final time !!!!!!!!!!
[17951.893248] <PINCHAR> : PINCHAR_ALLOCATE - Success(index = 0)
[17960.189583] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 27713, NAME = app_pinchar.bin> !!!
[17960.201128] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 10, Fragmentation Level = 98%
[17960.210269] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask : Allocation going via - slowpath !!!
[17960.335044] [HIGHERORDER_DEBUG] : did_some_progress = 887
[17960.339918] [HIGHERORDER_DEBUG] : Got some pages after direct reclaim .....
[17960.368939] <PINCHAR> : PINCHAR_ALLOCATE - Success(index = 4) !
[17964.518845] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 27713, NAME = app_pinchar.bin> !!!
[17964.530629] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 10, Fragmentation Level = 83%
[17964.547138] <PINCHAR> : PINCHAR_ALLOCATE - Success(index = 8) !
[17965.552976] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 27713, NAME = app_pinchar.bin> !!!
[17965.564319] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 10, Fragmentation Level = 84%
[17965.580823] <PINCHAR> : PINCHAR_ALLOCATE - Success(index = 9) !
[17966.586440] [HIGHERORDER_DEBUG] : __alloc_pages_nodemask is called by process <PID = 27713, NAME = app_pinchar.bin> !!!
[17966.597175] [HIGHERORDER_DEBUG] : ZONE : Normal, NODE : 0, ORDER = 10, Fragmentation Level = 85%
[17966.613424] <PINCHAR> : PINCHAR_ALLOCATE - Success(index = 10) !

Allocation failed directly during the first attempt itself even after direct reclaim. But after introducing a delay and retrying, all further allocation succeeded. May be Kswapd takes sometime to clear up dirty pages and buddy adding it back to free area.

Final Fragmentation Level

```
/opt/pintu # cat /proc/fraglevelinfo ; cat /proc/buddyinfo
Node:0, Zone:Normal
Order     FreePages         MovablePages     ReclaimablePages          Fragmentation[%]
  0         864                465                135                        0%
  1         863                583                118                        0%
  2         868                626                107                        2%
  3         659                493                 74                        5%
  4         566                434                 41                       10%
  5         358                280                 28                       18%
  6         222                184                 16                       28%
  7          90                 83                  6                       41%
  8          78                 67                  0                       51%
  9          13                 13                  0                       69%
 10          26                  0                  0                       75%
TotalFreePages: 110818
TotalMovablePages: 70191
TotalReclaimablePages: 4735
Overall Fragmentation: 27%

Node:0, Zone:HighMem
Order     FreePages         MovablePages     ReclaimablePages          Fragmentation[%]
  0        4579               4523                  0                        0%
  1        8239               8202                  0                        7%
  2        4789               4756                  0                       34%
  3        1760               1734                  0                       65%
  4         362                355                  0                       88%
  5          35                 32                  0                       97%
  6           4                  4                  0                       99%
  7           0                  0                  0                      100%
  8           0                  0                  0                      100%
  9           0                  0                  0                      100%
 10           0                  0                  0                      100%
TotalFreePages: 61461
TotalMovablePages: 60783
TotalReclaimablePages: 0
Overall Fragmentation: 71%

Node 0, zone   Normal    864    862    868    659    566    358    222     90     78     13     26
Node 0, zone  HighMem   4579   8239   4789   1760    362     35      4      0      0      0      0
```

Here you can see lots of movable pages after lots of direct reclaim. Thus direct compact might be helpful after direct reclaim and not before.

EXPERIMENTATION DATA

Page Order	Block Used	Available Blocks	No of Blocks Requested	Current Fragmentation Level	No of Blocks Allocated	Pass Rate
10	1024	0	20	100%	20	100%
9	512	11	20	94%	20	100%
8	256	4	20	90%	20	100%
8	256	0	50	100%	50	100%
9	512	1	30	97%	30	100%
10	1024	28	40	10%	40	100%
10	1024	0	50	100%	46	92%

DATA COLLECTED ON :

Kernel 2.6.32 [DRAM 512MB, no swap]

SUMMARY

- **Measuring fragmentation level and tracking higher-order is important at least for low memory notifier.**
- **It was observed that allocation takes slowpath whenever fragmentation level is above 90%.**
- **The delay introduced here is only for experimental purpose.**
  - **Delay could be because, dirty pages has to be written to the disk before it is marked freed.**
  - **May be the real thing could be to wait till lazy buddy allocator rearranges the free pages.**
  - **This is valid only for GFP_KERNEL where a sleep is allowed.**

- **Can we introduce something like system wide fragmentation level across all zones???**
  - **As shown in the experimental data in previous slides**
  - **Auto recovery if fragmentation crosses > 90%**
- **From kernel2.6.35 COMPACTION contains its own fragmentation level measurement.**
  - **/sys/kernel/debug/extfrag/unusable_index**
  - **But this requires COMPACTION and HUGETLB to be enabled.**
  - **May be we can utilize this from kernel2.6.35 onwards.**
  - **Difficult to back port compaction to lower kernel version.**
  - **Mostly helpful for user space allocation where pages are movable.**

- **Reserving memory during boot time using CMA can reduce fragmentation to some extent.**
  - **But good only if we have bigger RAM.**
- **But sometimes CMA region itself suffers from memory fragmentation and may again requires help of compaction to move pages.**
  - **May be we can introduce a new ZONE such as CMA_ZONE for all CMA memory allocation.**
- **Is rebooting the only option left?. Can we do something else?**
- **Further investigation is in progress.**

- ***Memory fragmentation is like a decease which can only be prevented and cannot be cured.***

- ***Therefore extra care needs to be taken while designing your system itself.***

Some References

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Thank You !!!