US008606903B2

(12) **United States Patent**
Al-Wakeel et al.

(10) **Patent No.: US 8,606,903 B2**
(45) **Date of Patent: Dec. 10, 2013**

(54) **COOPERATIVE PACKET ROUTING FOR WIRELESS SENSOR NETWORKS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 878 days.

(21) Appl. No.: **12/328,662**

(22) Filed: **Dec. 4, 2008**

(65) **Prior Publication Data**

US 2010/0142422 A1 Jun. 10, 2010

(51) **Int. Cl.**

G06F 15/173	(2006.01)
G06F 15/16	(2006.01)

(52) **U.S. Cl.**
USPC **709/224**; 709/245; 709/241; 709/242

(58) **Field of Classification Search**
USPC 709/224, 241, 242, 245
See application file for complete search history.

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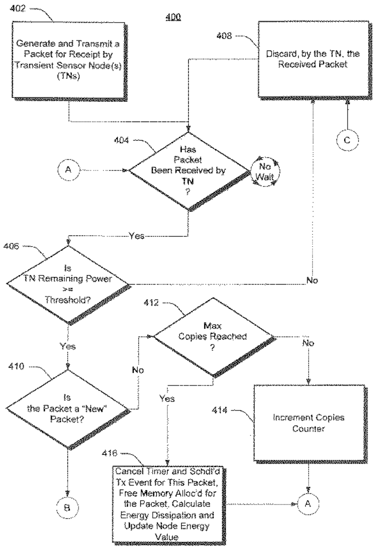
(74) *Attorney, Agent, or Firm* — Hart IP Law & Strategies

(57) **ABSTRACT**

A cooperative packet routing for wireless sensor networks is described. In one aspect, a transient sensor node in a wireless sensor network receives a packet from a source node, wherein the packet is targeted for receipt by a base station. The transient sensor node, responsive to receiving the packet, estimates how much operational energy remains in the sensor node. If the determined amount of energy meets a configurable threshold, the transient sensor node implements a set of cooperative packet routing operations for conditional re-transmission of the packet to the base station. The configurable threshold is set to ensure substantially optimal usage and lifetime of the sensor node in the wireless sensor network. The conditional re-transmission of the packet is based on a set of randomized packet re-transmission criteria.

18 Claims, 48 Drawing Sheets
(43 of 48 Drawing Sheet(s) Filed in Color)



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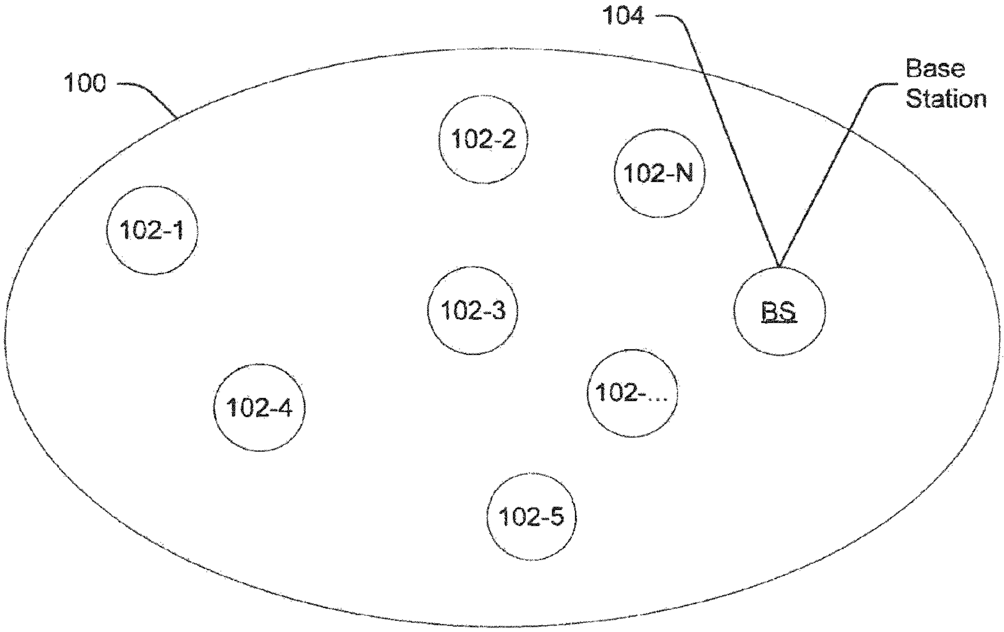

Fig. 1

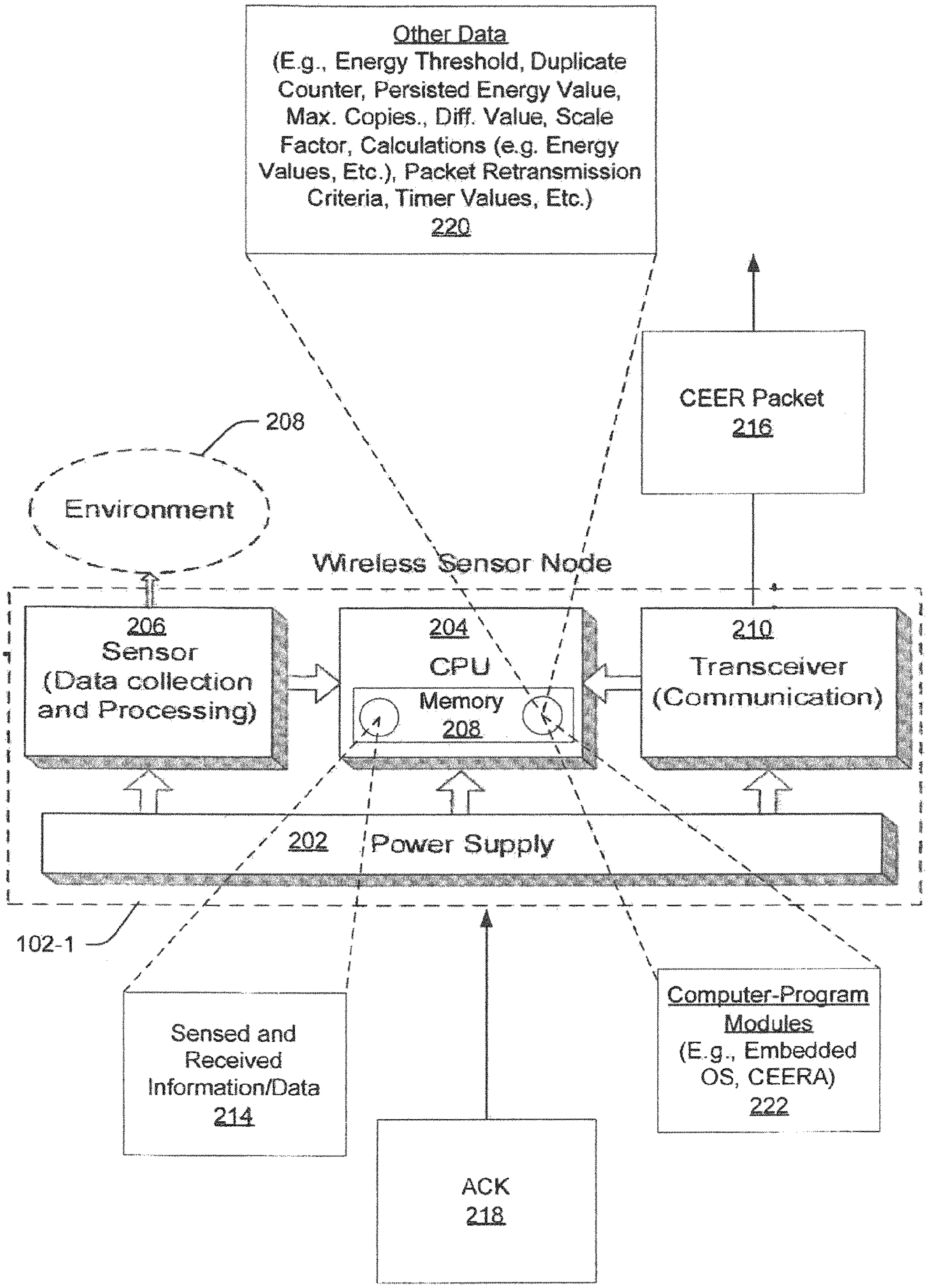
Other Data
(E.g., Energy Threshold, Duplicate Counter, Persisted Energy Value, Max. Copies., Diff. Value, Scale Factor, Calculations (e.g. Energy Values, Etc.), Packet Retransmission Criteria, Timer Values, Etc.)
220
CEER Packet
216
208
Environment
Wireless Sensor Node
206
Sensor
(Data collection and Processing)
204
CPU
Memory
208
210
Transceiver
(Communication)
202
Power Supply
102-1
Sensed and Received Information/Data
214
ACK
218
Computer-Program Modules
(E.g., Embedded OS, CEERA)
222

Fig. 2

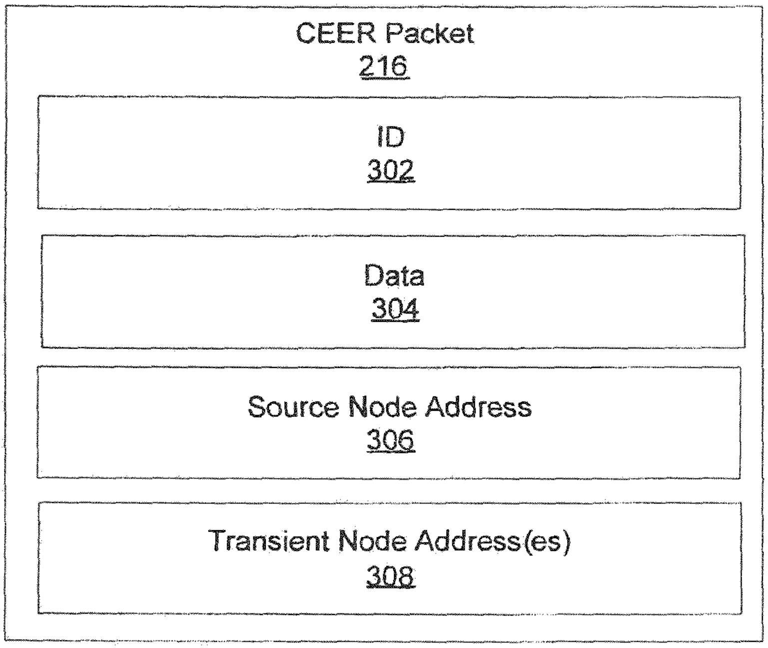
CEER Packet
216
ID
302
Data
304
Source Node Address
306
Transient Node Address(es)
308

Fig. 3

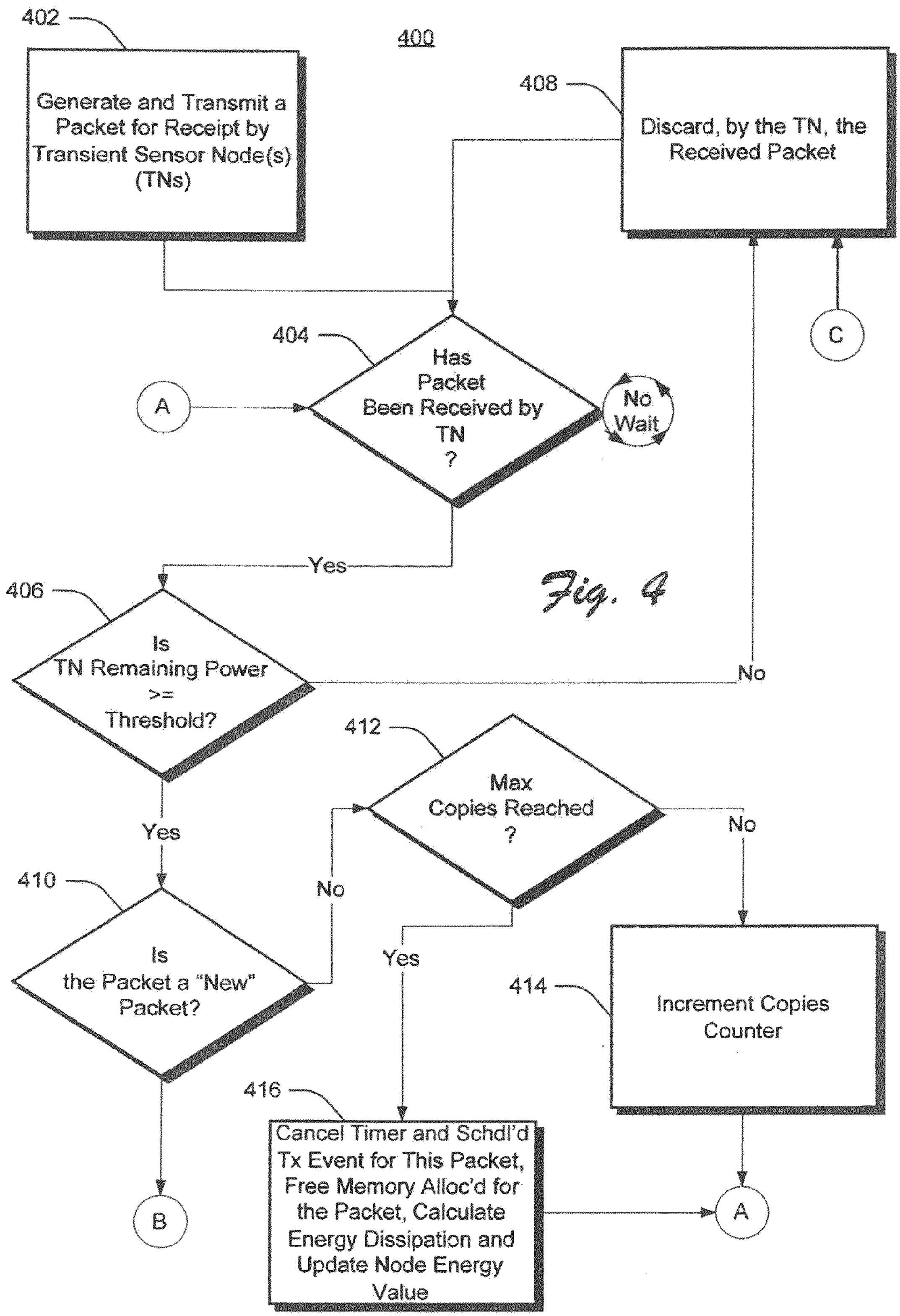
400
402
Generate and Transmit a Packet for Receipt by Transient Sensor Node(s) (TNs)
408
Discard, by the TN, the Received Packet
404
Has Packet Been Received by TN ?
A
No Wait
C
Yes
406
Is TN Remaining Power >= Threshold?
No
412
Max Copies Reached ?
No
Yes
410
Is the Packet a "New" Packet?
No
Yes
414
Increment Copies Counter
416
Cancel Timer and Schdl'd Tx Event for This Packet, Free Memory Alloc'd for the Packet, Calculate Energy Dissipation and Update Node Energy Value
B
A

Fig. 4

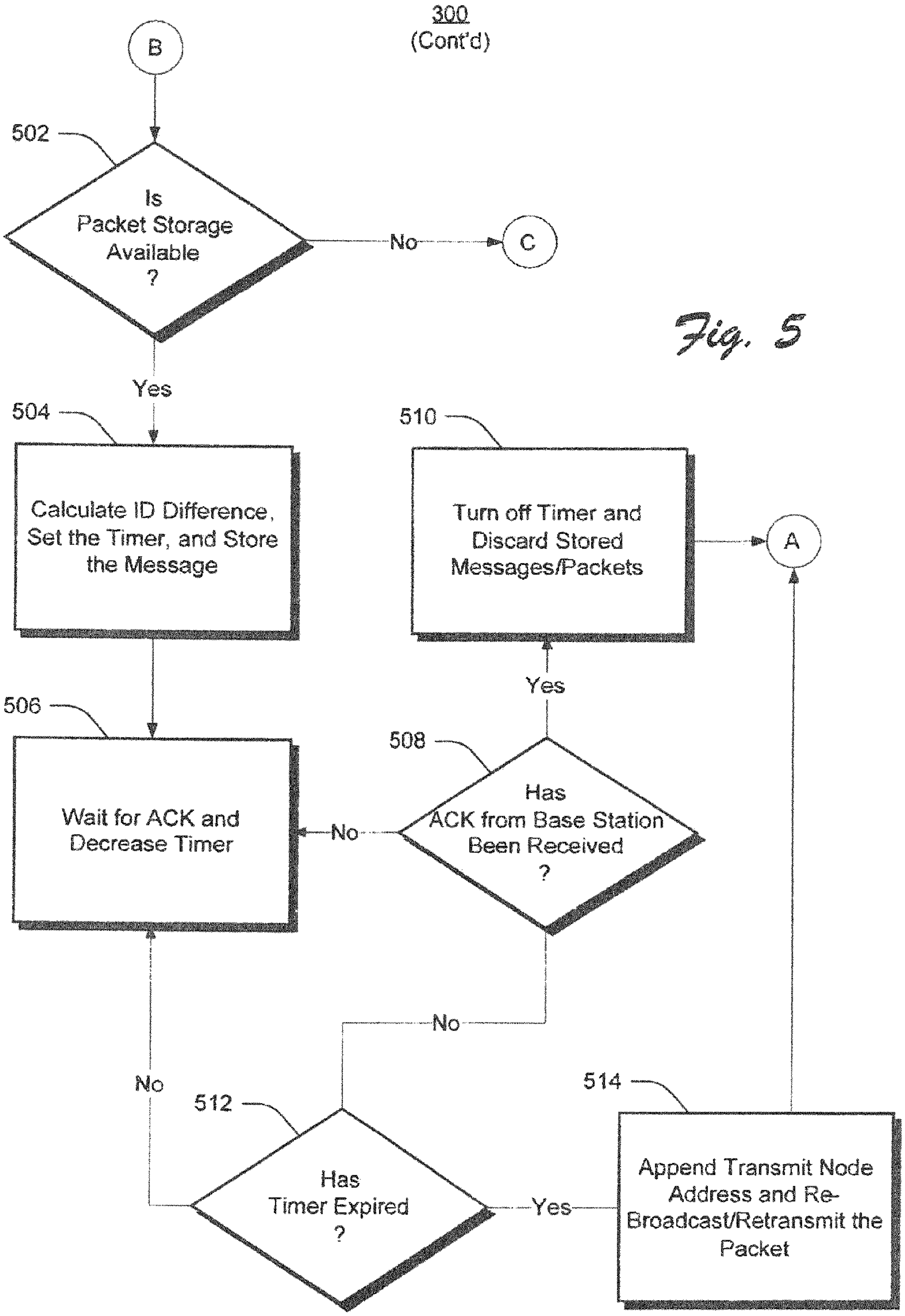
300
(Cont'd)
B
502
Is Packet Storage Available ?
No
C
Yes
504
Calculate ID Difference, Set the Timer, and Store the Message
510
Turn off Timer and Discard Stored Messages/Packets
A
506
Wait for ACK and Decrease Timer
Yes
508
Has ACK from Base Station Been Received ?
No
No
No
512
Has Timer Expired ?
Yes
514
Append Transmit Node Address and Re-Broadcast/Retransmit the Packet

Fig. 5

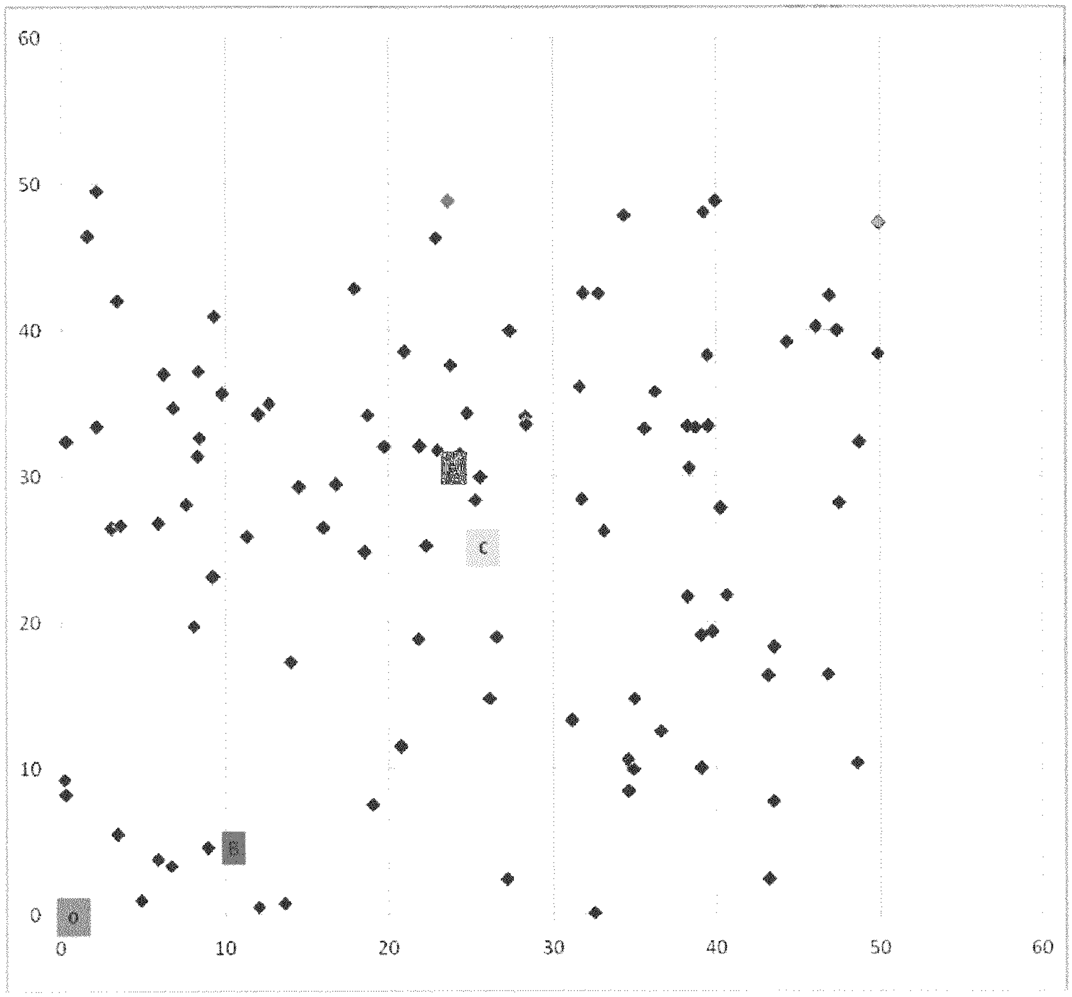

Fig. 6

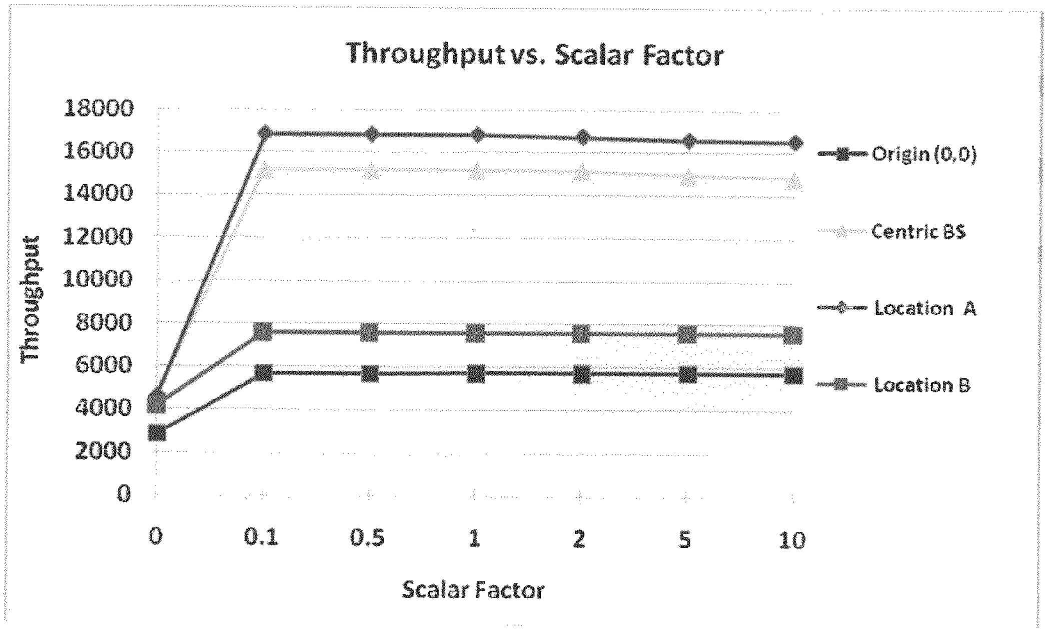
Throughput vs. Scalar Factor
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Throughput
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 7

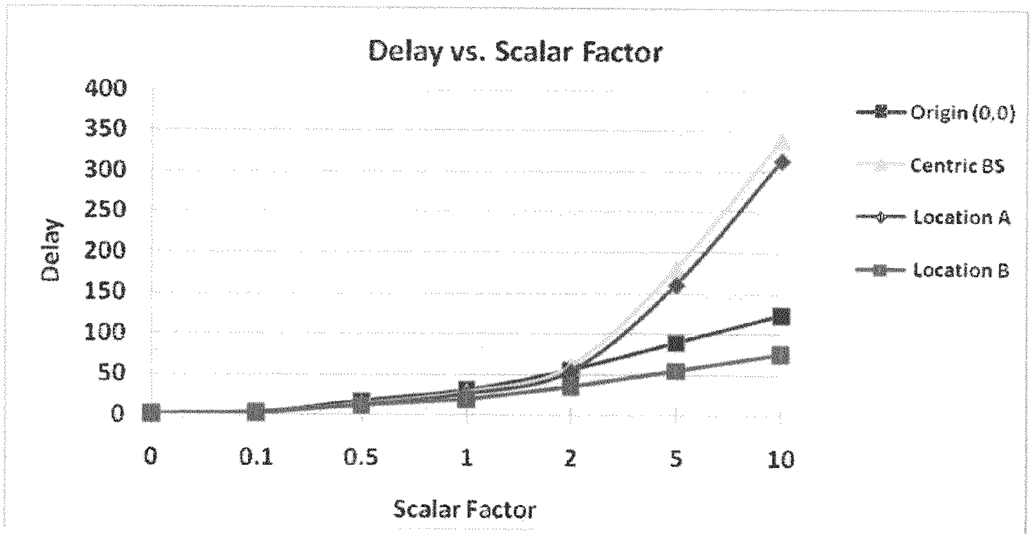
Delay vs. Scalar Factor
400
350
300
250
200
150
100
50
0
Delay
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 8

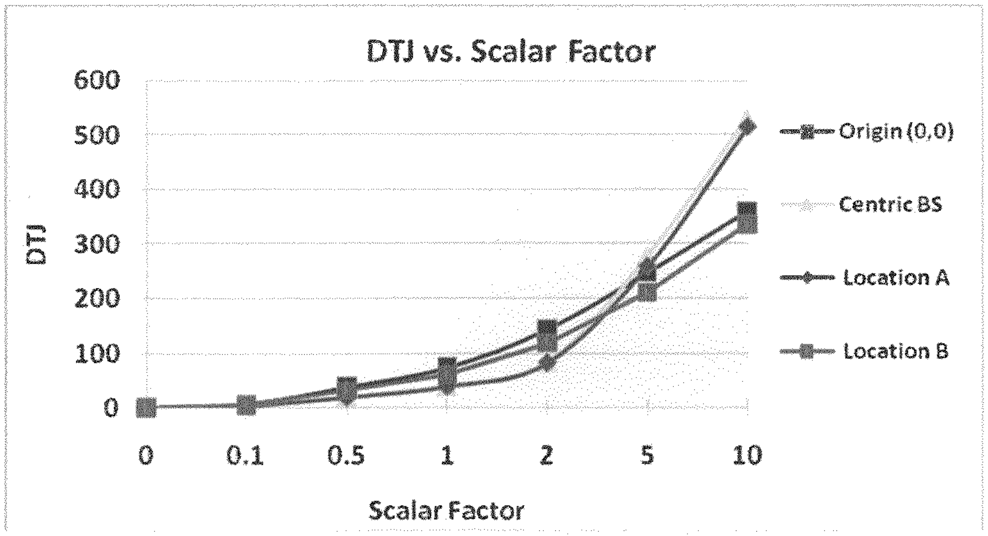
DTJ vs. Scalar Factor
600
500
400
300
200
100
0
DTJ
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 9

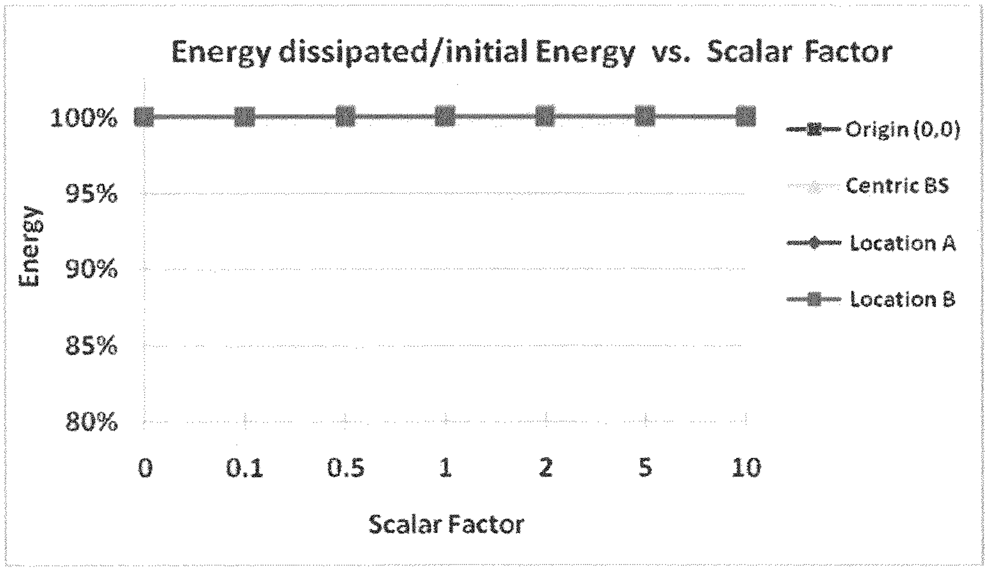
Energy dissipated/initial Energy vs. Scalar Factor
100%
95%
90%
85%
80%
Energy
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 10

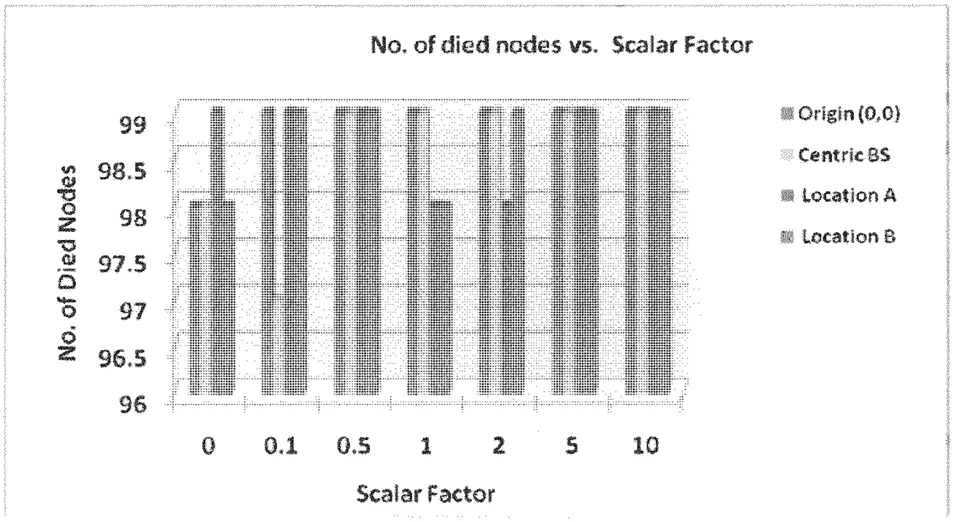
No. of died nodes vs. Scalar Factor
No. of Died Nodes
99
98.5
98
97.5
97
96.5
96
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 11

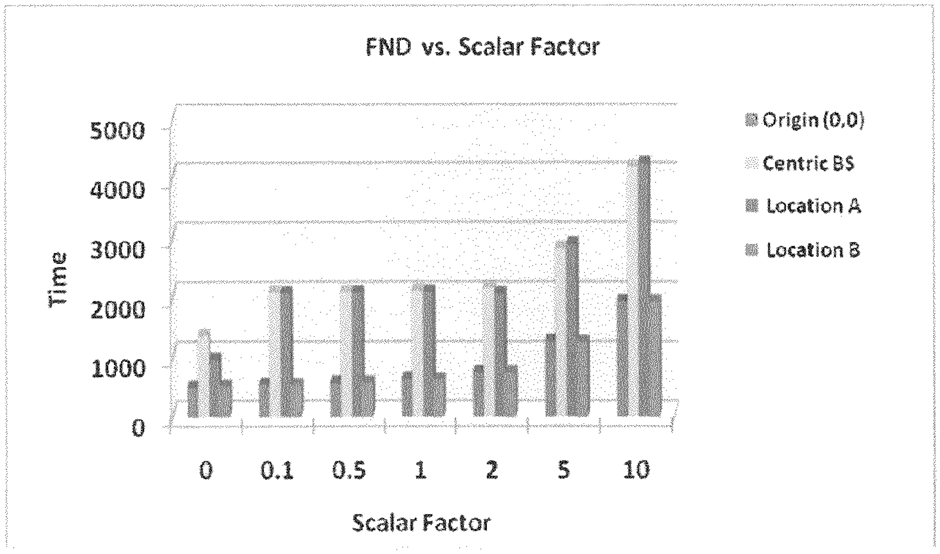
FND vs. Scalar Factor
Time
5000
4000
3000
2000
1000
0
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 12

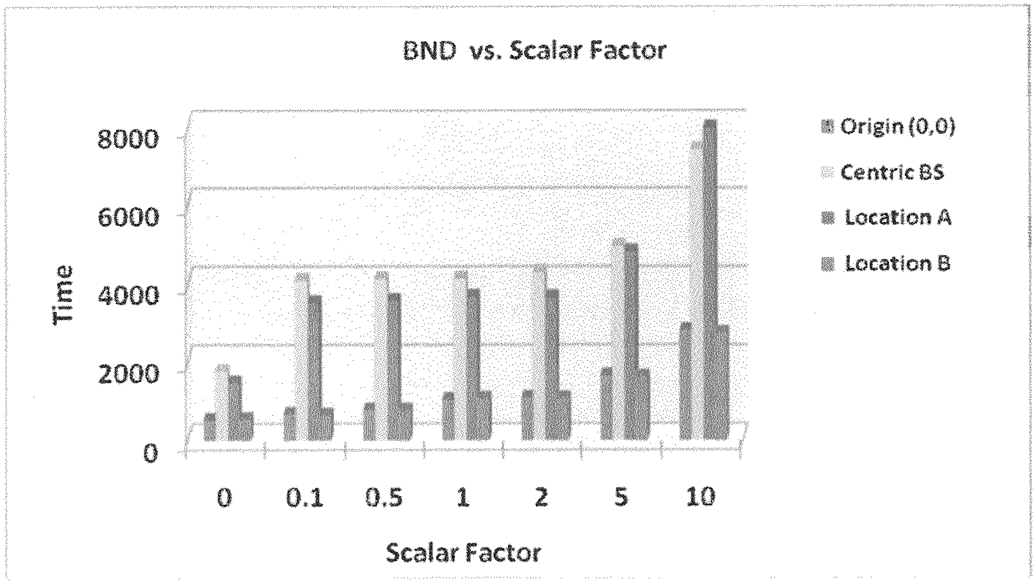
BND vs. Scalar Factor
8000
6000
4000
2000
0
Time
0
0.1
0.5
1
2
5
10
Scalar Factor
▨ Origin (0,0)
▨ Centric BS
▨ Location A
▨ Location B

Fig. 13

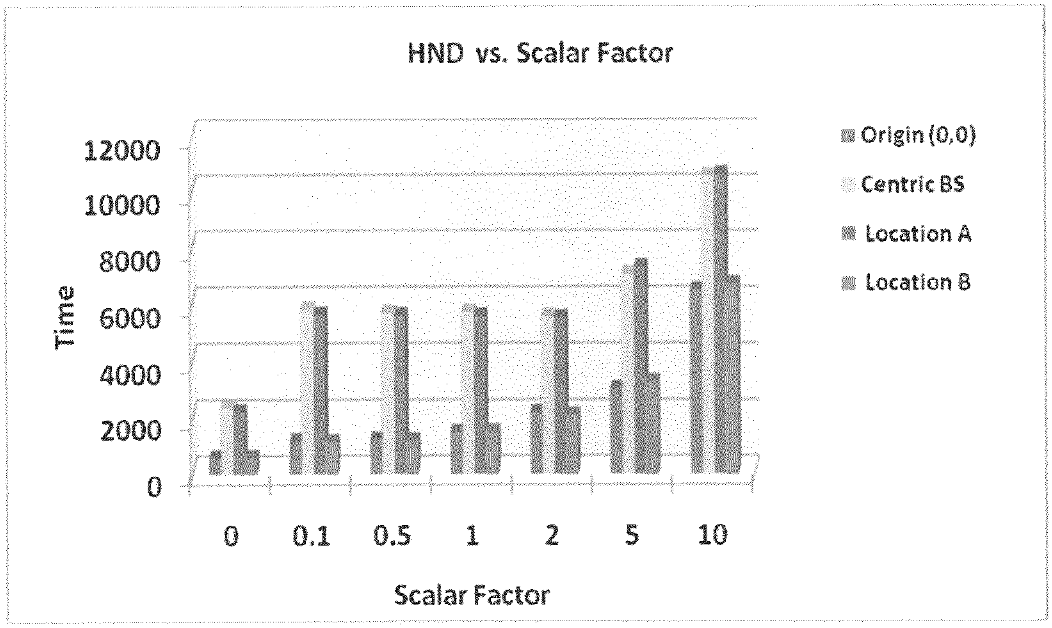
HND vs. Scalar Factor
12000
10000
8000
6000
4000
2000
0
Time
0
0.1
0.5
1
2
5
10
Scalar Factor
▨ Origin (0,0)
▨ Centric BS
▨ Location A
▨ Location B

Fig. 14

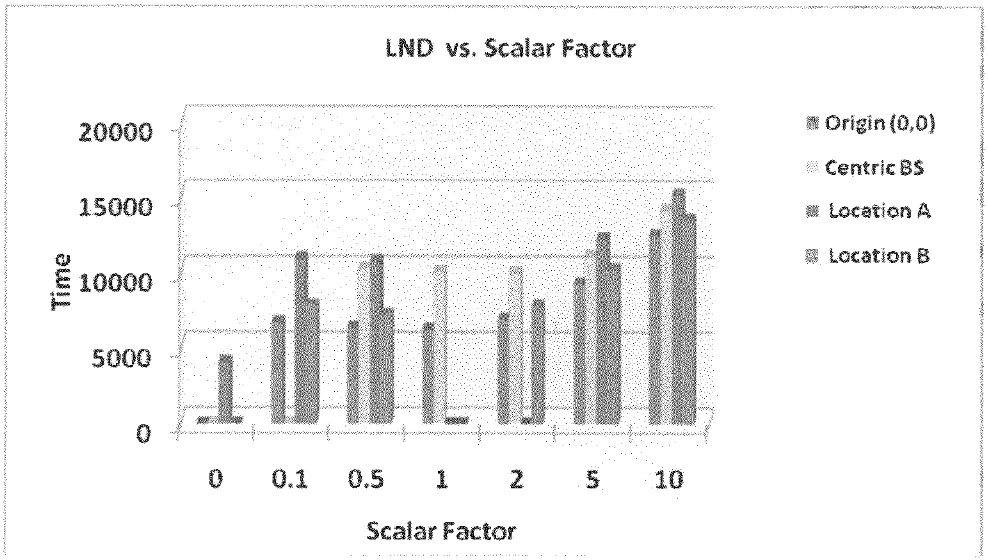
LND vs. Scalar Factor
20000
15000
10000
5000
0
Time
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 15

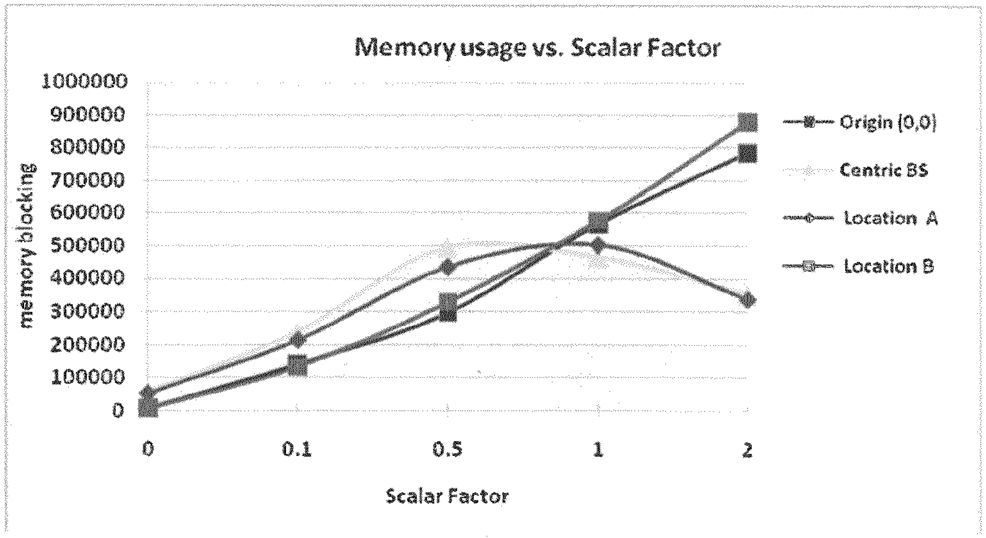
Memory usage vs. Scalar Factor
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
memory blocking
0
0.1
0.5
1
2
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 16

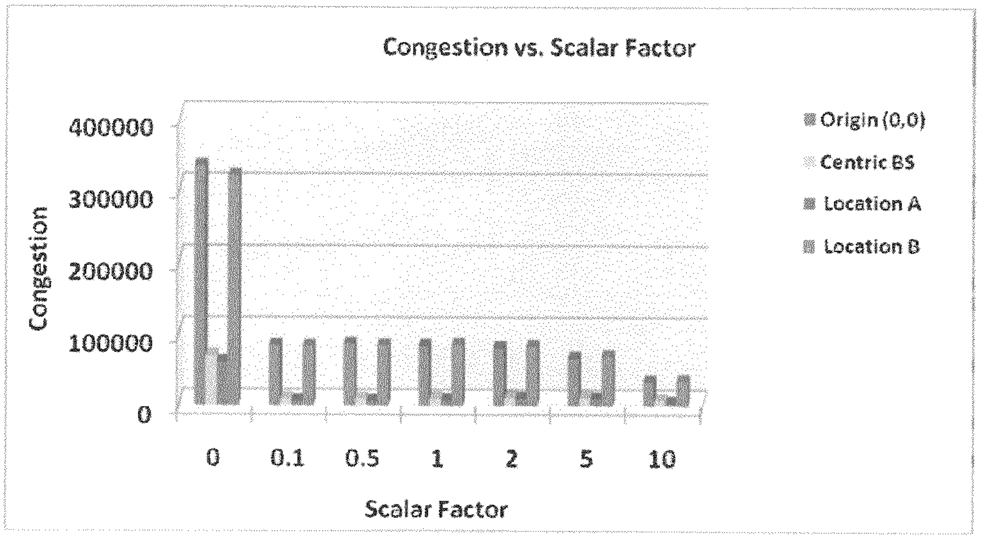
Congestion vs. Scalar Factor
400000
300000
200000
100000
0
Congestion
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 17

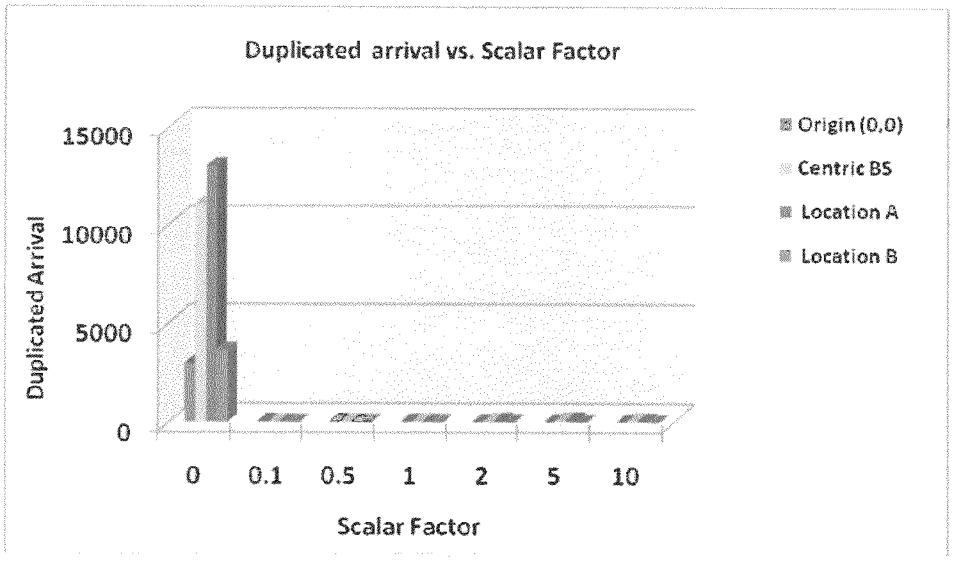
Duplicated arrival vs. Scalar Factor
15000
10000
5000
0
Duplicated Arrival
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 18

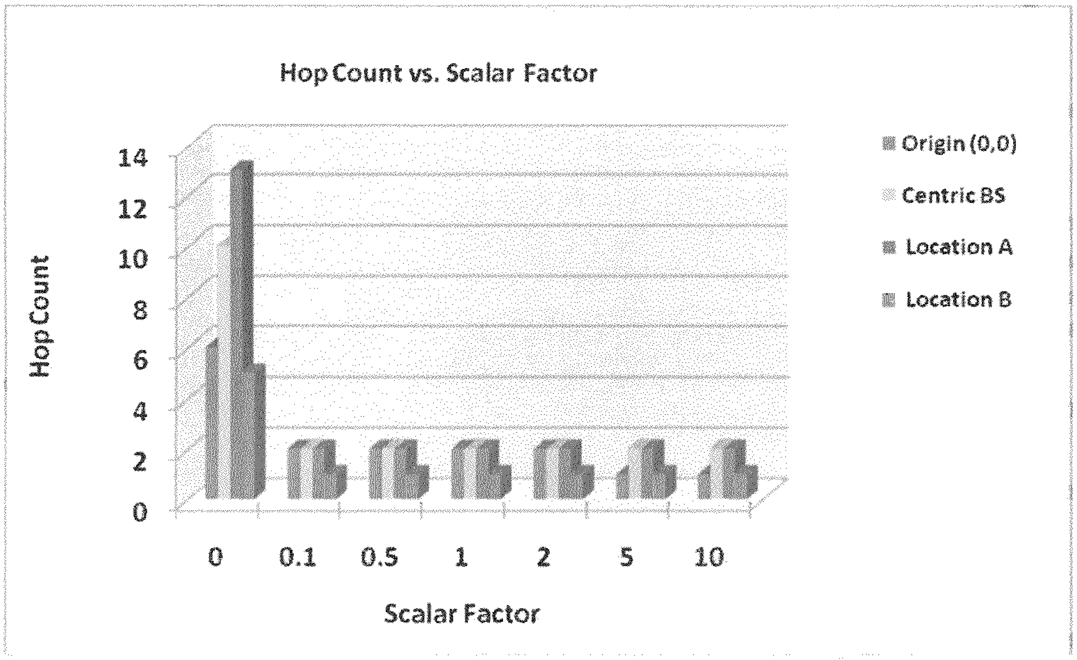
Hop Count vs. Scalar Factor
Hop Count
14
12
10
8
6
4
2
0
0
0.1
0.5
1
2
5
10
Scalar Factor
Origin (0,0)
Centric BS
Location A
Location B

Fig. 19

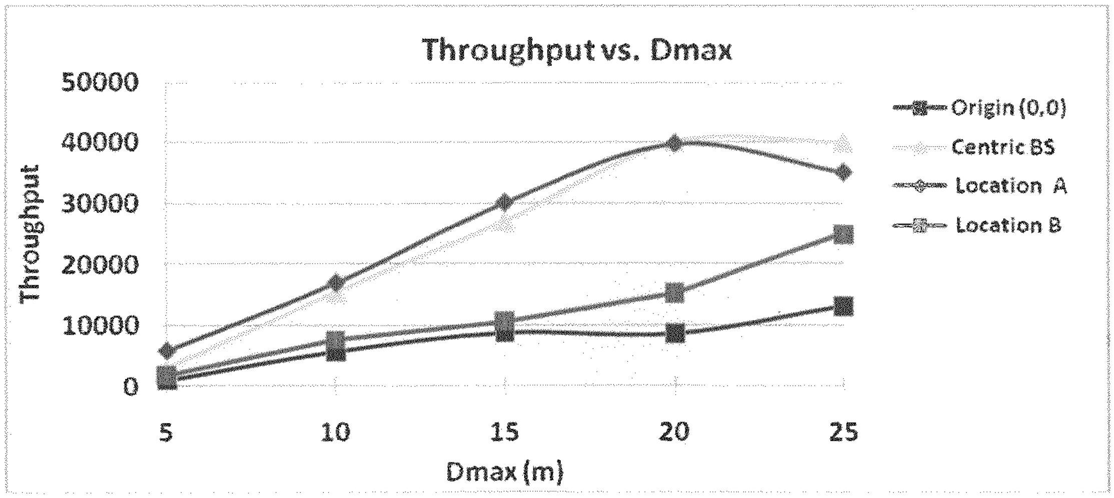
Throughput vs. Dmax
Throughput
50000
40000
30000
20000
10000
0
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 20

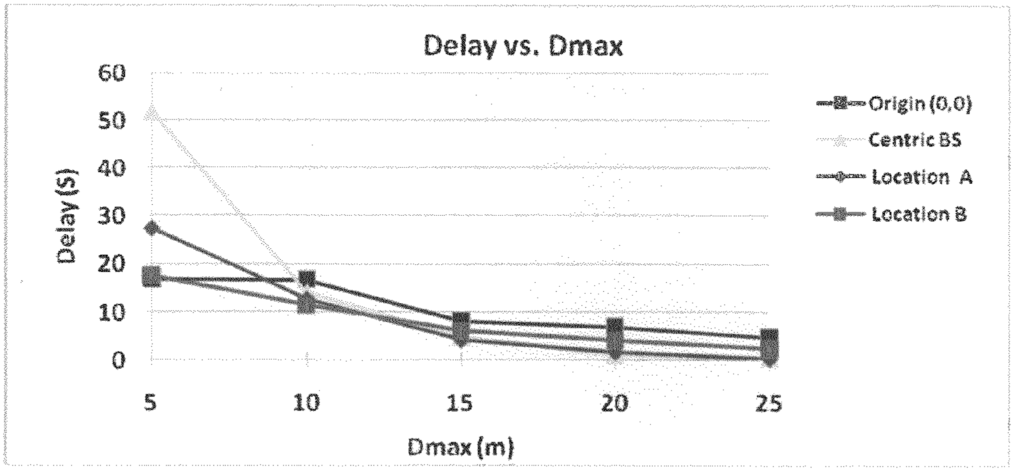
Delay vs. Dmax
60
50
40
30
20
10
0
Delay ($)
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 21

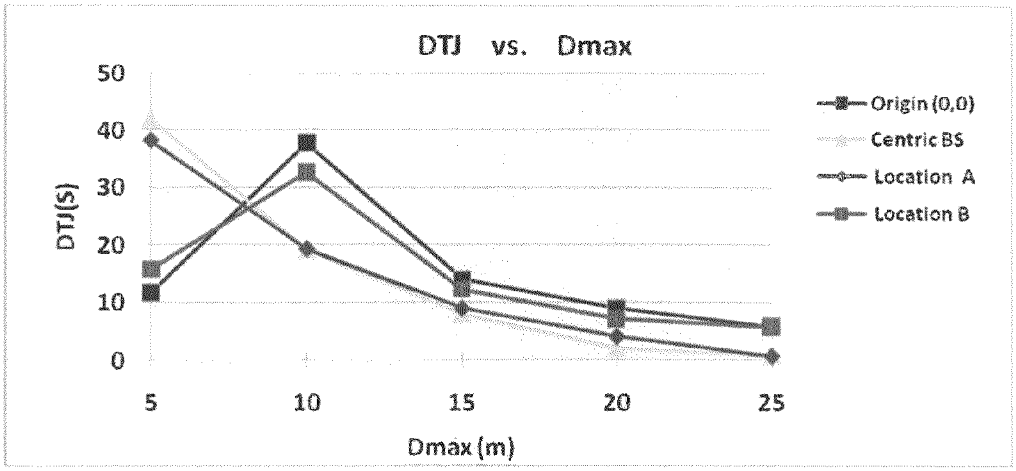
DTJ vs. Dmax
50
40
30
20
10
0
DTJ($)
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 22

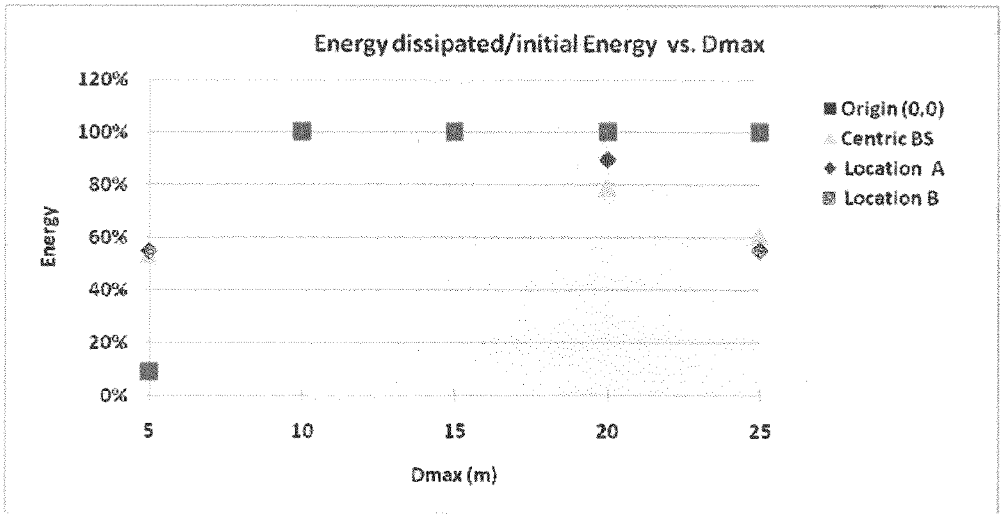
Energy dissipated/initial Energy vs. Dmax
120%
100%
80%
60%
40%
20%
0%
Energy
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 23

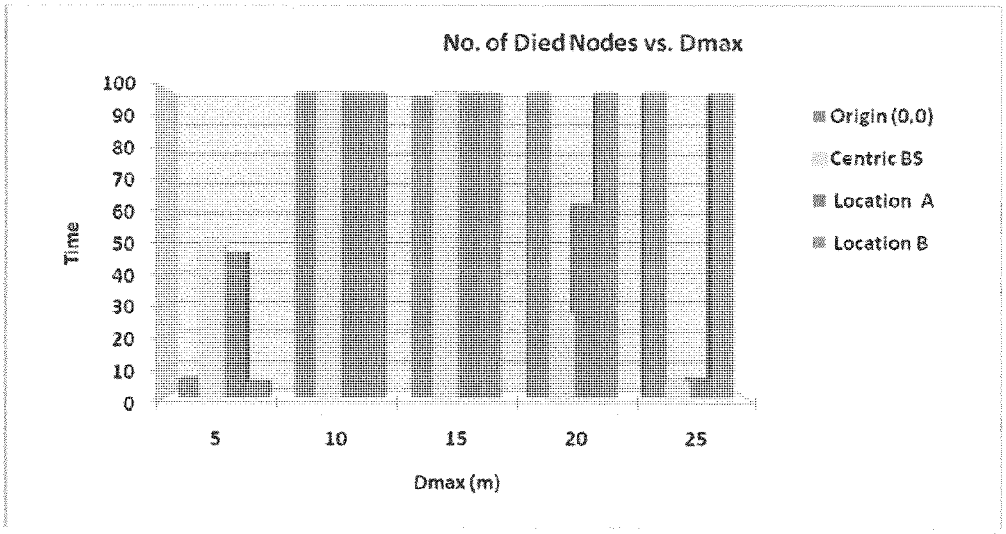
No. of Died Nodes vs. Dmax
100
90
80
70
60
50
40
30
20
10
0
Time
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 24

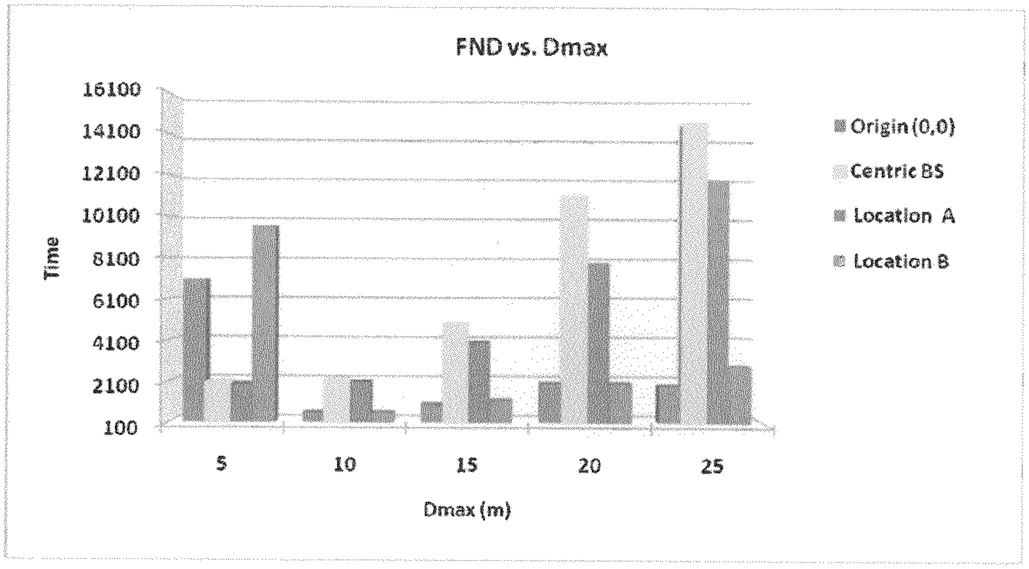
FND vs. Dmax
Time
16100
14100
12100
10100
8100
6100
4100
2100
100
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 25

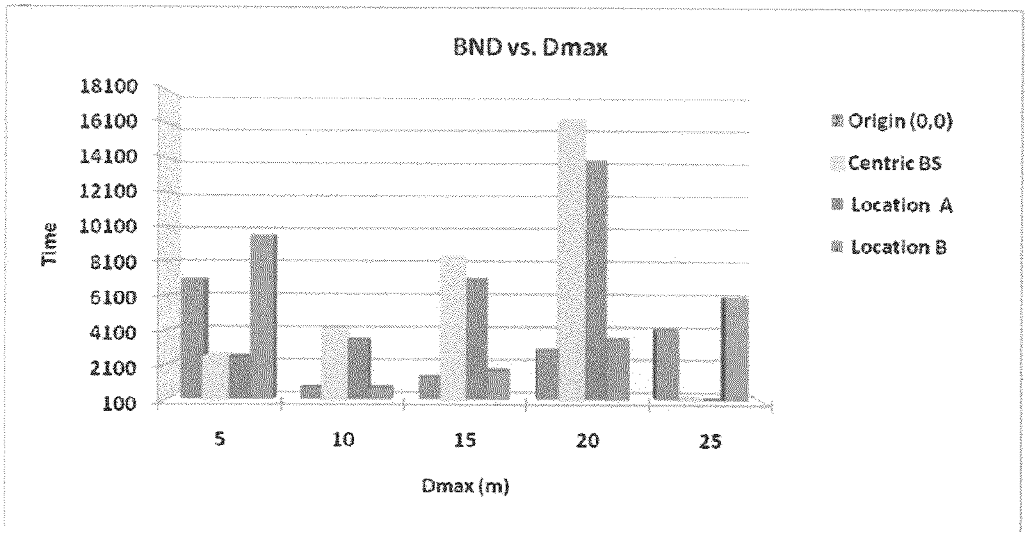
BND vs. Dmax
Time
18100
16100
14100
12100
10100
8100
6100
4100
2100
100
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 26

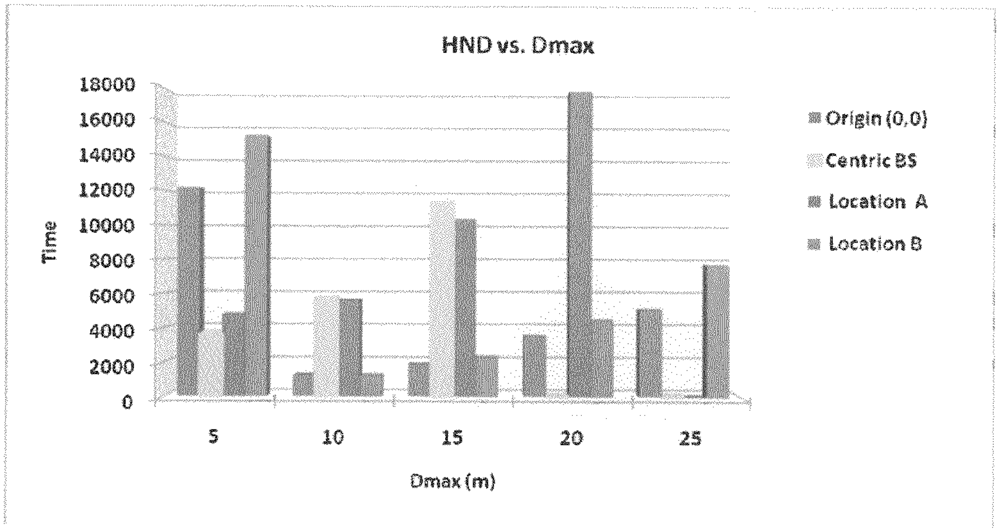
HND vs. Dmax
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Time
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 27

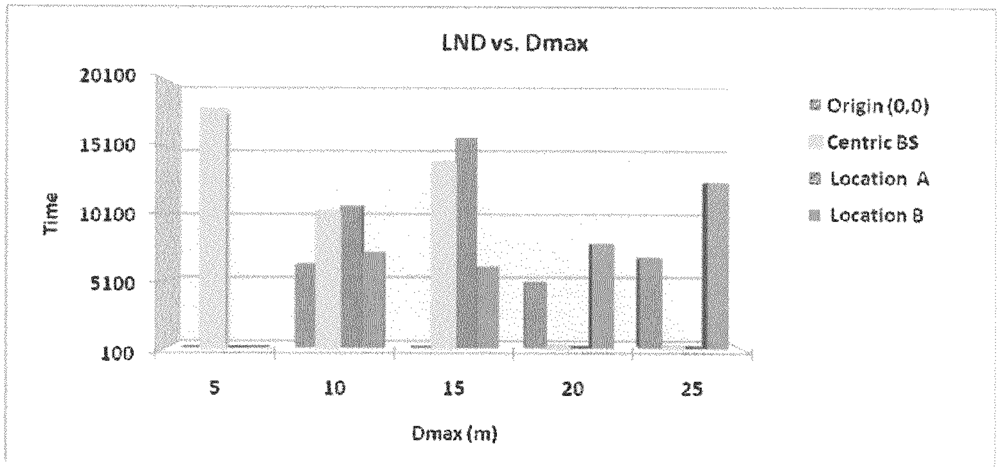
LND vs. Dmax
20100
15100
10100
5100
100
Time
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 28

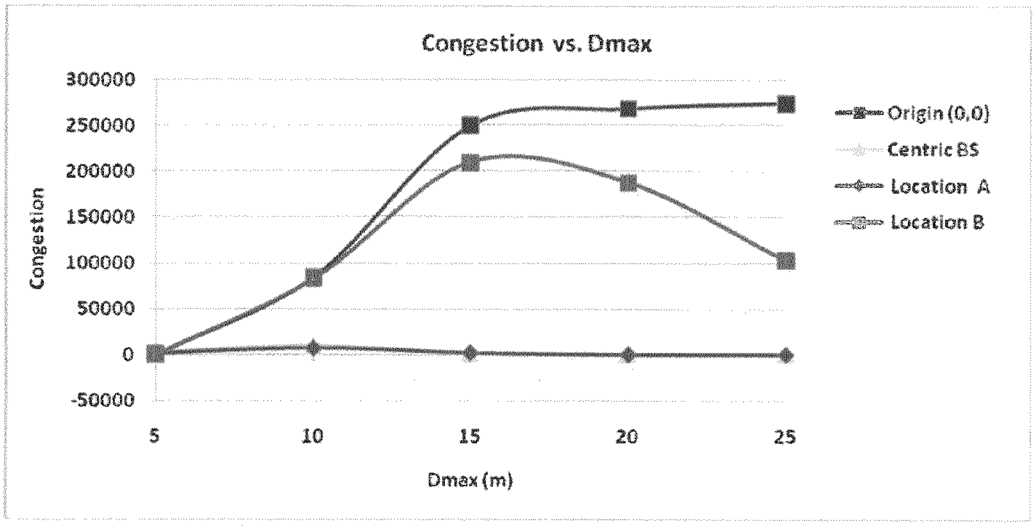
Congestion vs. Dmax
300000
250000
200000
150000
100000
50000
0
-50000
Congestion
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 29

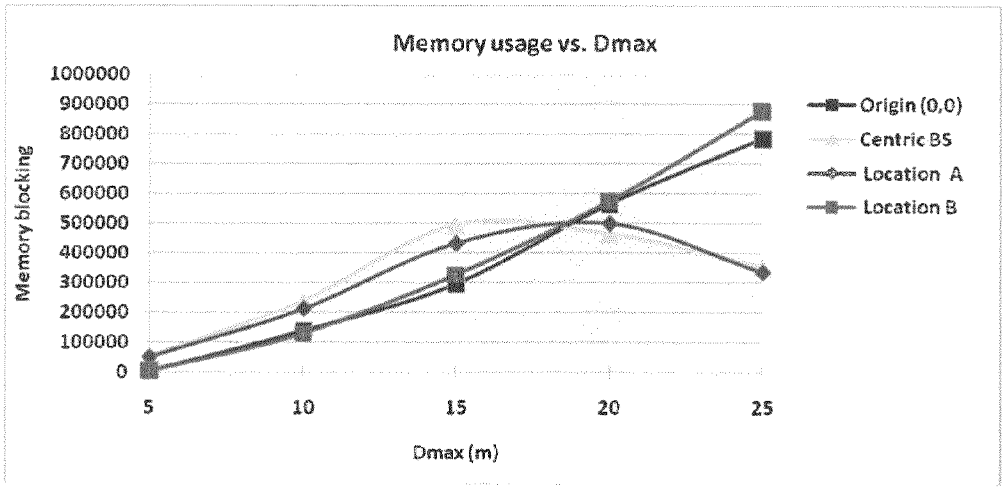
Memory usage vs. Dmax
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
Memory blocking
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 30

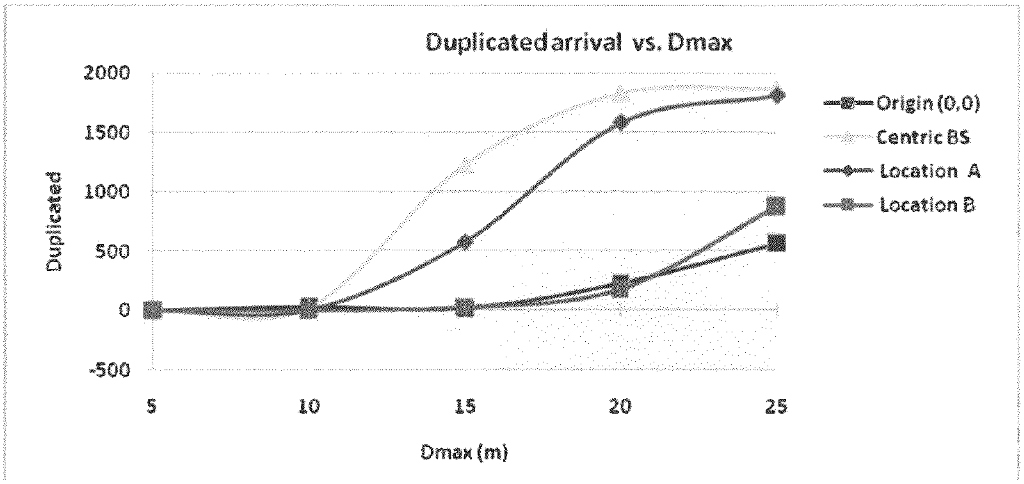
Duplicated arrival vs. Dmax
2000
1500
1000
500
0
-500
Duplicated
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 31

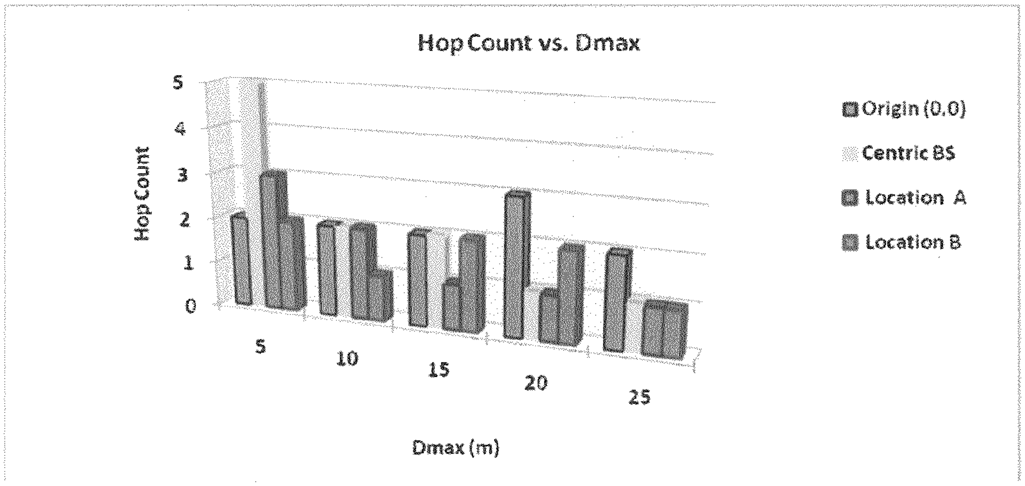
Hop Count vs. Dmax
5
4
3
2
1
0
Hop Count
5
10
15
20
25
Dmax (m)
Origin (0,0)
Centric BS
Location A
Location B

Fig. 32

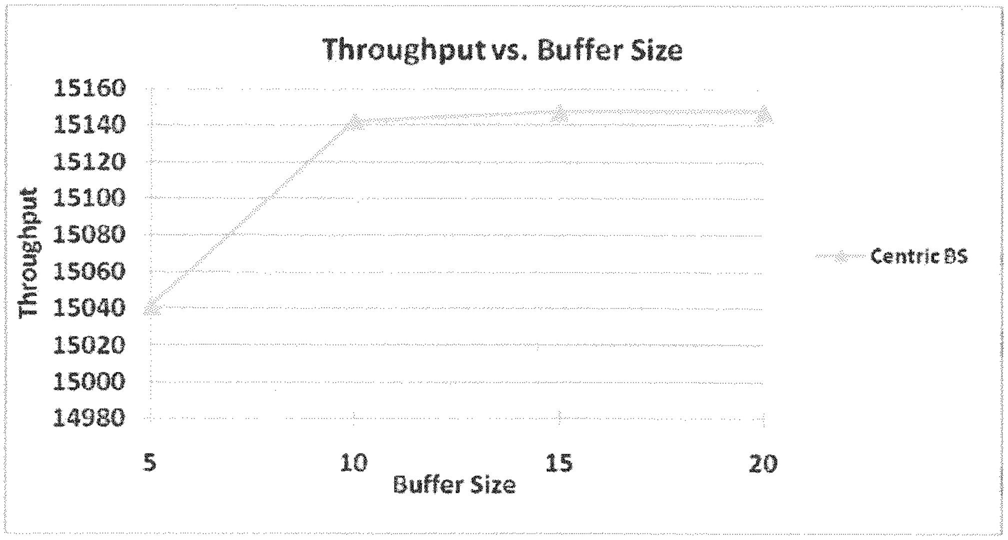
Throughput vs. Buffer Size
Throughput
15160
15140
15120
15100
15080
15060
15040
15020
15000
14980
5
10
15
20
Buffer Size
Centric BS

Fig. 33

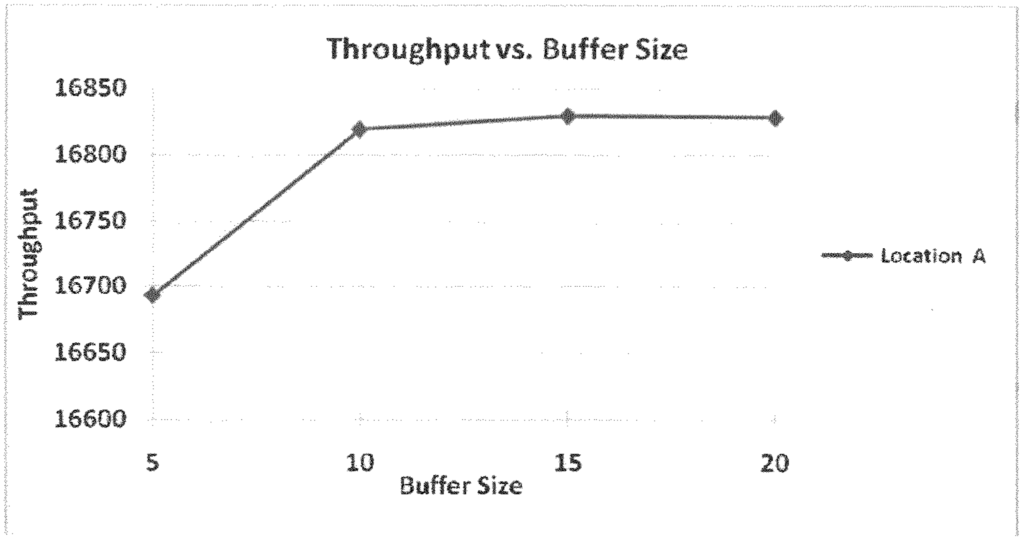
Throughput vs. Buffer Size
Throughput
16850
16800
16750
16700
16650
16600
5
10
15
20
Buffer Size
Location A

Fig. 34

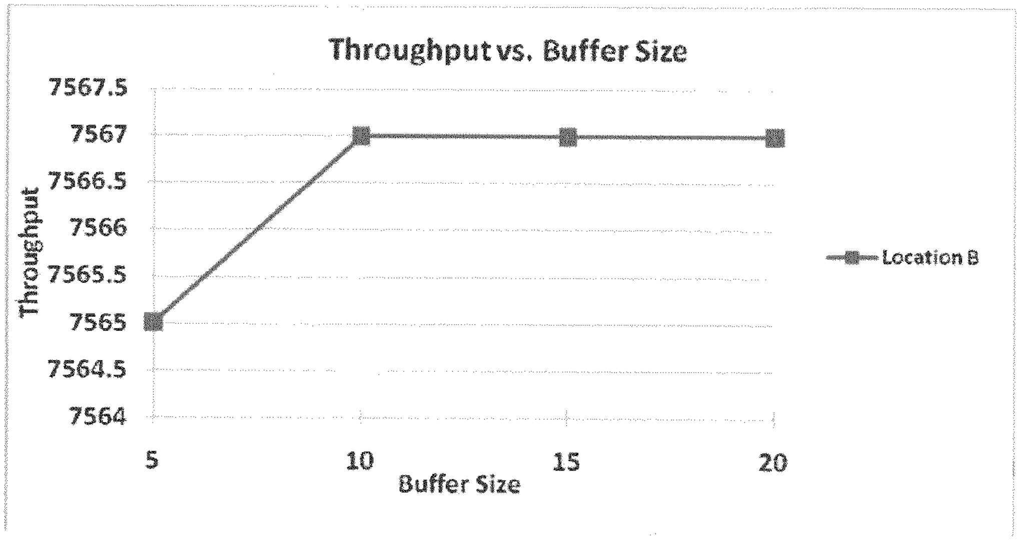
Throughput vs. Buffer Size
7567.5
7567
7566.5
7566
7565.5
7565
7564.5
7564
Throughput
5
10
15
20
Buffer Size
Location B

Fig. 35

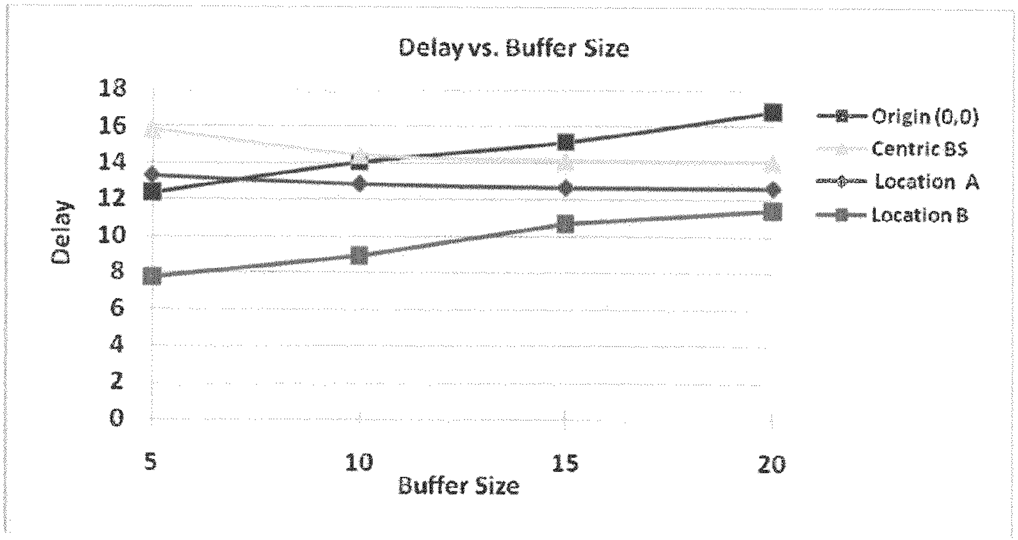
Delay vs. Buffer Size
18
16
14
12
10
8
6
4
2
0
Delay
5
10
15
20
Buffer Size
Origin (0,0)
Centric BS
Location A
Location B

Fig. 36

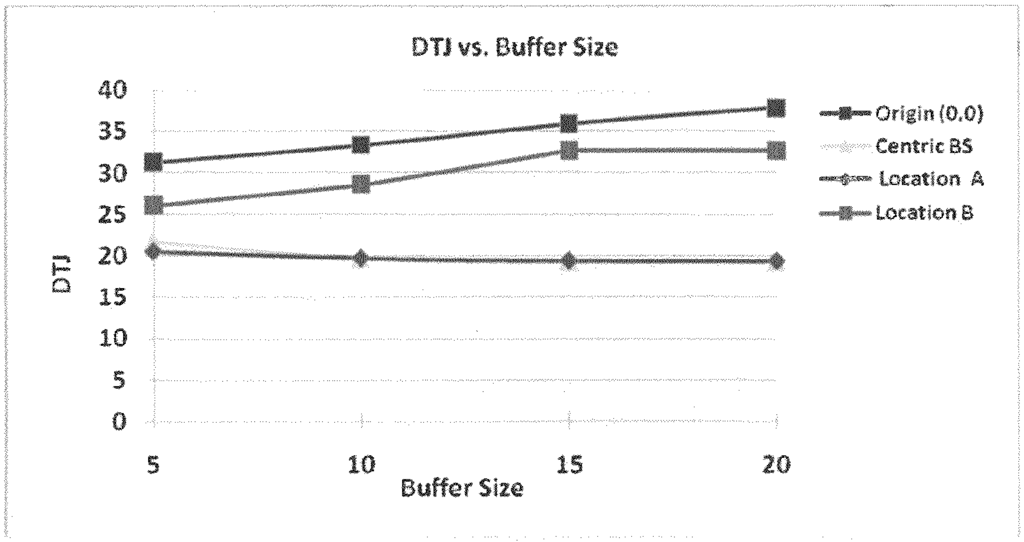
DTJ vs. Buffer Size
DTJ
40
35
30
25
20
15
10
5
0
5
10
15
20
Buffer Size
Origin (0,0)
Centric BS
Location A
Location B

Fig. 37

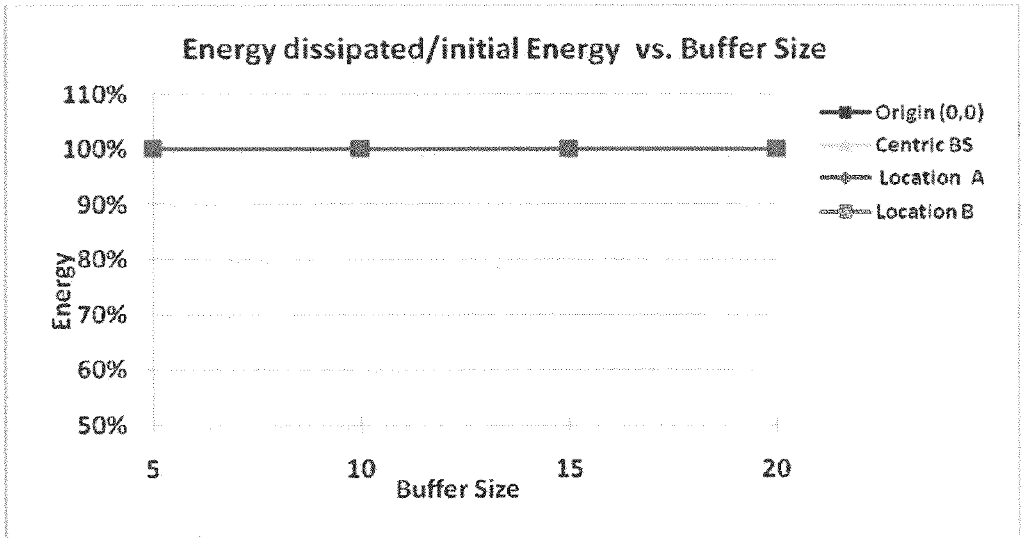
Energy dissipated/initial Energy vs. Buffer Size
Energy
110%
100%
90%
80%
70%
60%
50%
5
10
15
20
Buffer Size
Origin (0,0)
Centric BS
Location A
Location B

Fig. 38

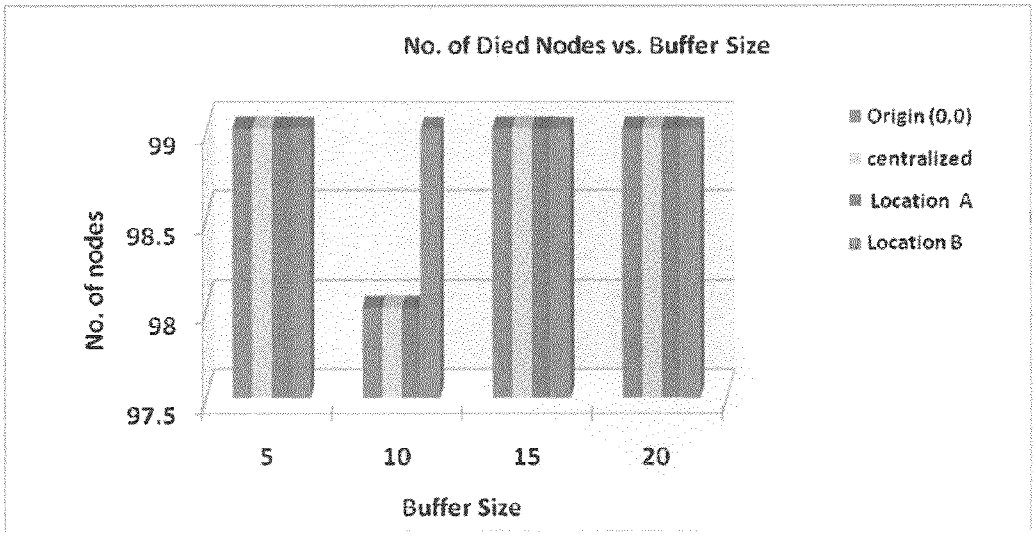
No. of Died Nodes vs. Buffer Size
No. of nodes
99
98.5
98
97.5
5
10
15
20
Buffer Size
Origin (0,0)
centralized
Location A
Location B

Fig. 39

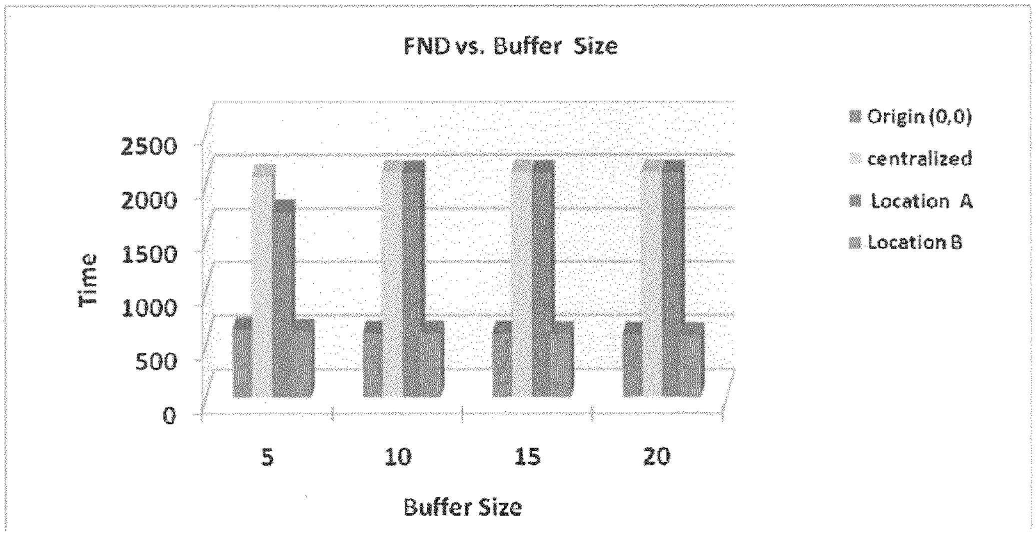
FND vs. Buffer Size
Time
2500
2000
1500
1000
500
0
5
10
15
20
Buffer Size
Origin (0,0)
centralized
Location A
Location B

Fig. 40

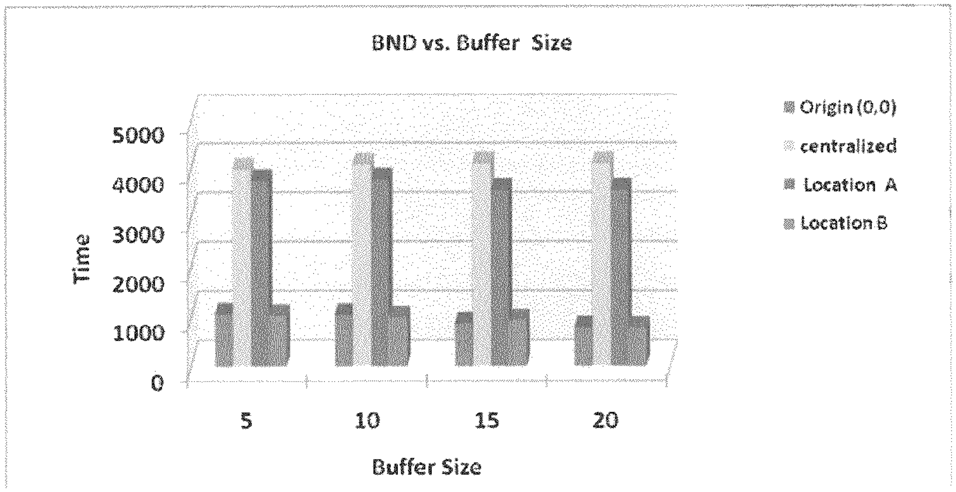
BND vs. Buffer Size
Time
5000
4000
3000
2000
1000
0
5
10
15
20
Buffer Size
Origin (0,0)
centralized
Location A
Location B

Fig. 41

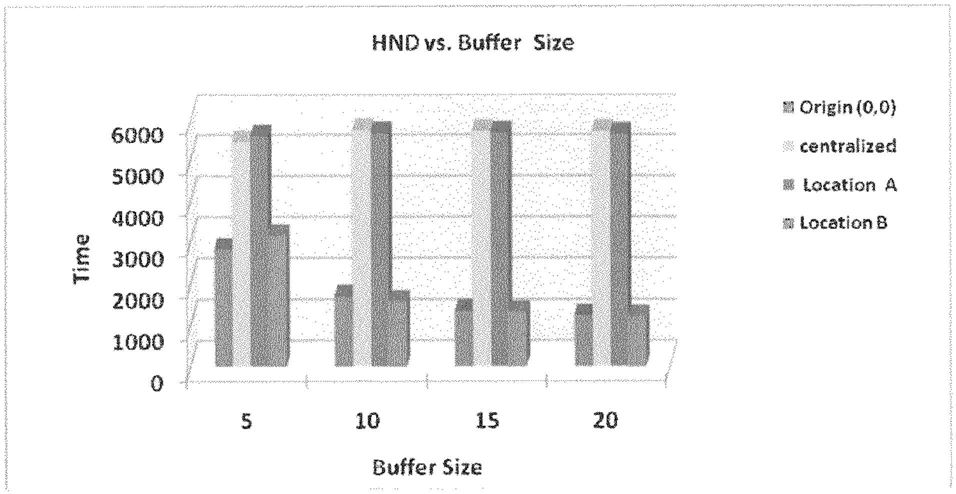
HND vs. Buffer Size
Time
6000
5000
4000
3000
2000
1000
0
5
10
15
20
Buffer Size
Origin (0,0)
centralized
Location A
Location B

Fig. 42

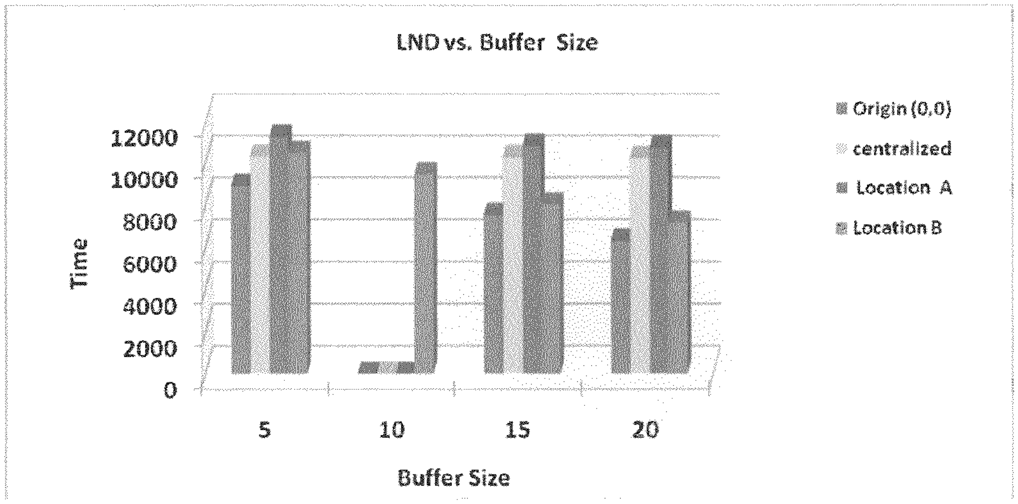
LND vs. Buffer Size
Time
12000
10000
8000
6000
4000
2000
0
5
10
15
20
Buffer Size
Origin (0,0)
centralized
Location A
Location B

Fig. 43

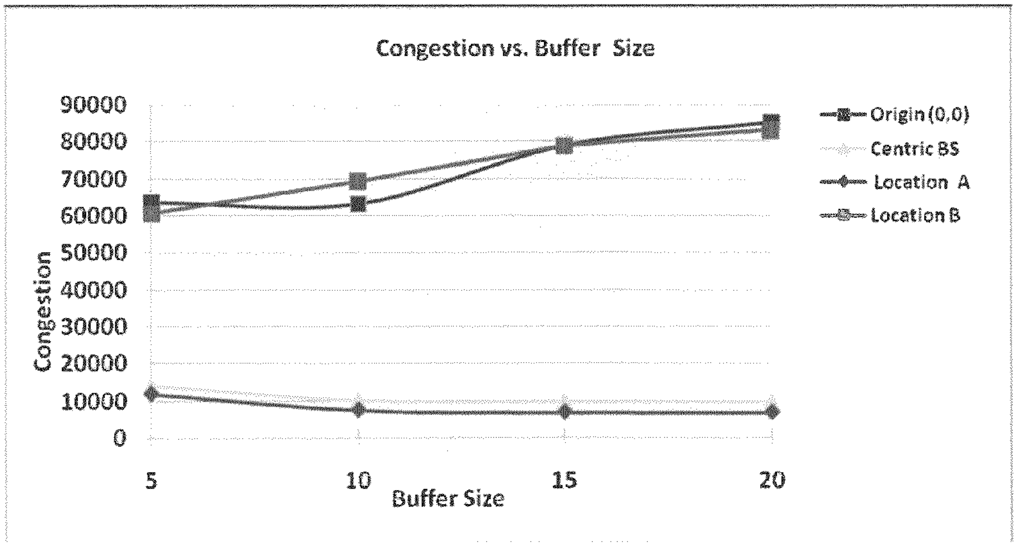
Congestion vs. Buffer Size
Congestion
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
5
10
15
20
Buffer Size
Origin (0,0)
Centric BS
Location A
Location B

Fig. 44

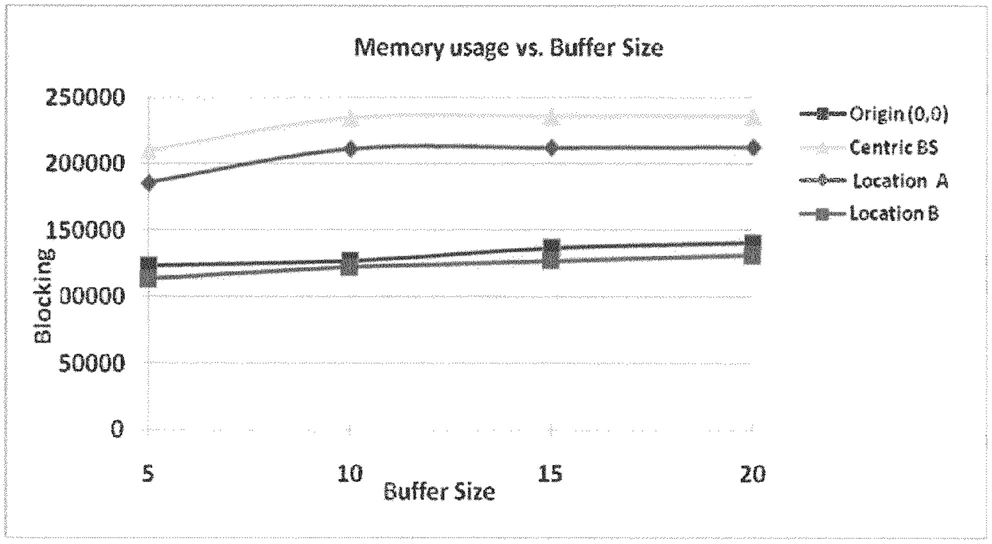
Memory usage vs. Buffer Size
250000
200000
150000
00000
50000
0
Blocking
5
10
15
20
Buffer Size
Origin (0,0)
Centric BS
Location A
Location B

Fig. 45

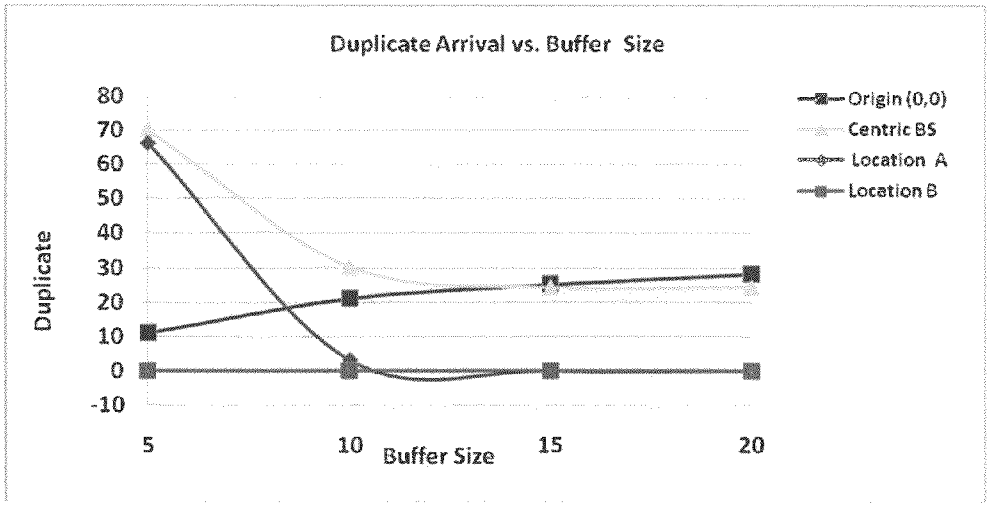
Duplicate Arrival vs. Buffer Size
80
70
60
50
40
30
20
10
0
-10
Duplicate
5
10
15
20
Buffer Size
Origin (0,0)
Centric BS
Location A
Location B

Fig. 46

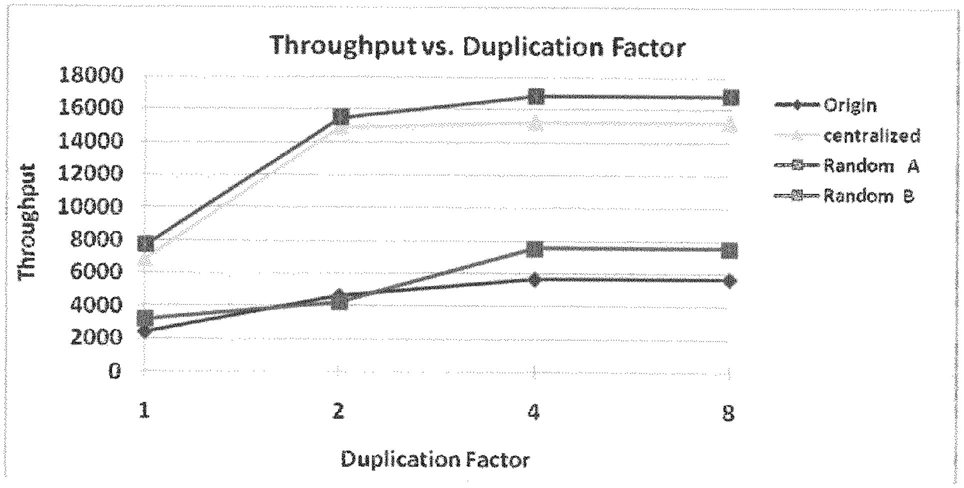
Throughput vs. Duplication Factor
Throughput
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1
2
4
8
Duplication Factor
Origin
centralized
Random A
Random B

Fig. 47

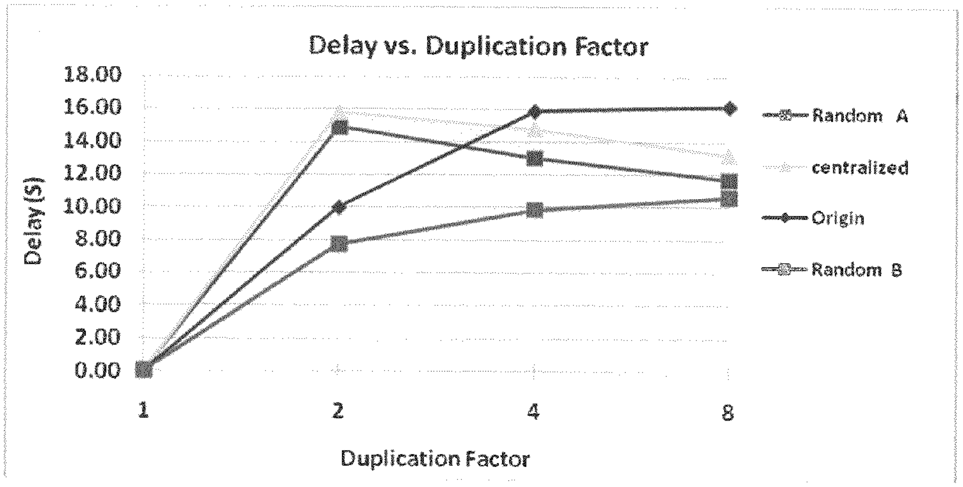
Delay vs. Duplication Factor
Delay (S)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
2
4
8
Duplication Factor
Random A
centralized
Origin
Random B

Fig. 48

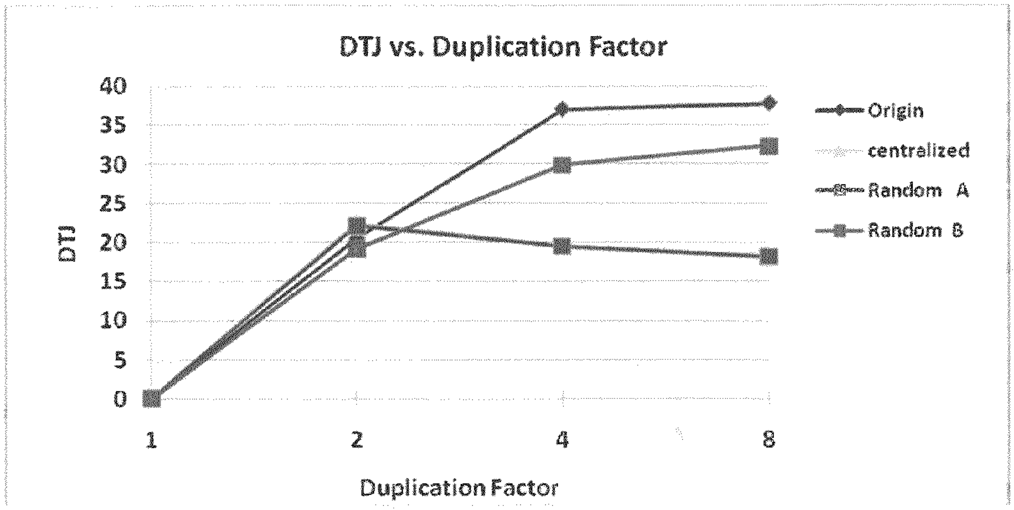
DTJ vs. Duplication Factor
40
35
30
25
20
15
10
5
0
DTJ
1
2
4
8
Duplication Factor
Origin
centralized
Random A
Random B

Fig. 49

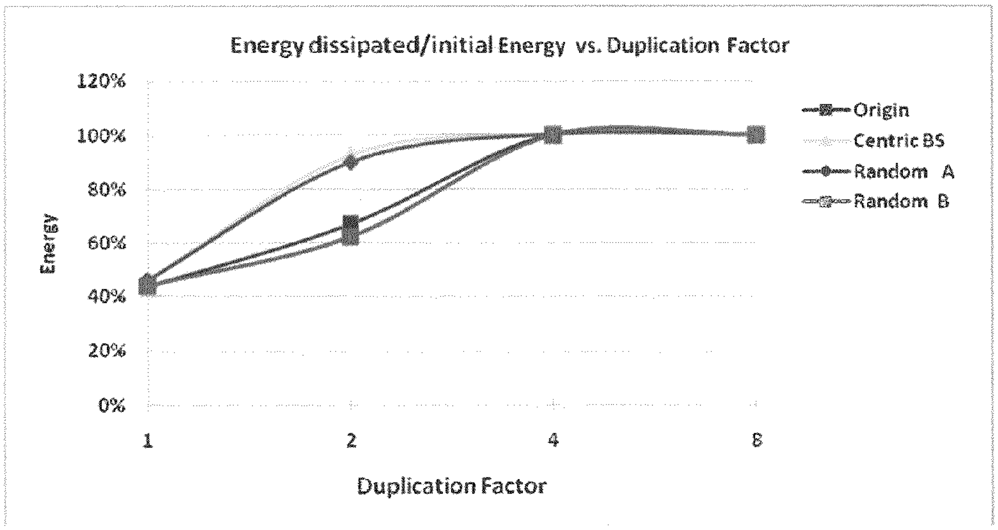
Energy dissipated/initial Energy vs. Duplication Factor
120%
100%
80%
60%
40%
20%
0%
Energy
1
2
4
8
Duplication Factor
Origin
Centric BS
Random A
Random B

Fig. 50

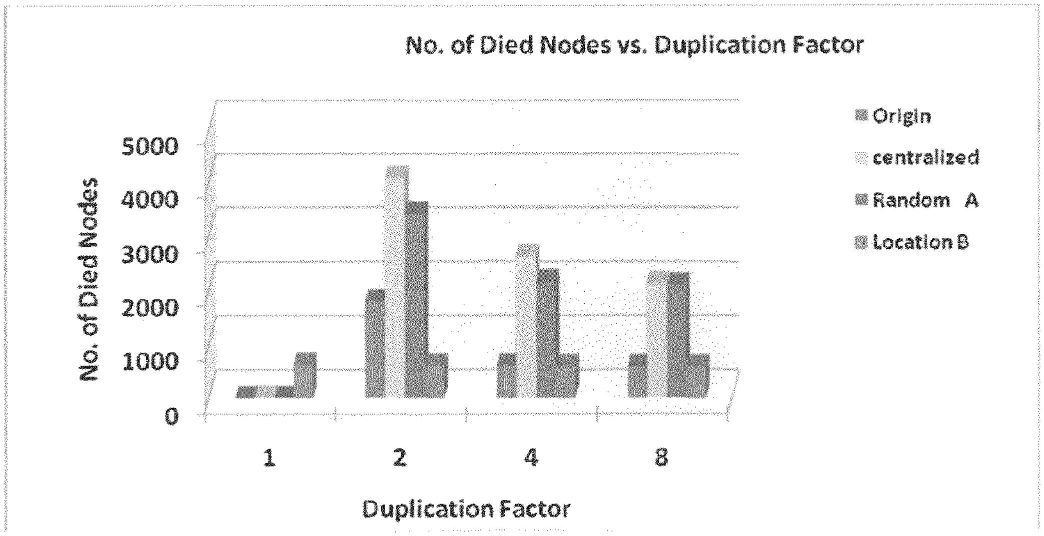
No. of Died Nodes vs. Duplication Factor
No. of Died Nodes
5000
4000
3000
2000
1000
0
1
2
4
8
Duplication Factor
Origin
centralized
Random A
Location B

Fig. 51

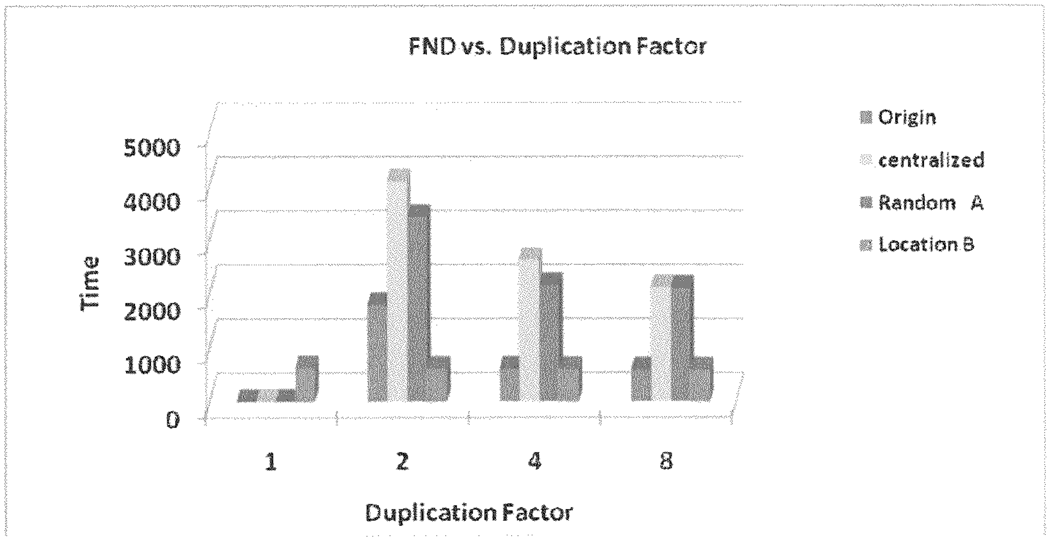
FND vs. Duplication Factor
Time
5000
4000
3000
2000
1000
0
1
2
4
8
Duplication Factor
Origin
centralized
Random A
Location B

Fig. 52

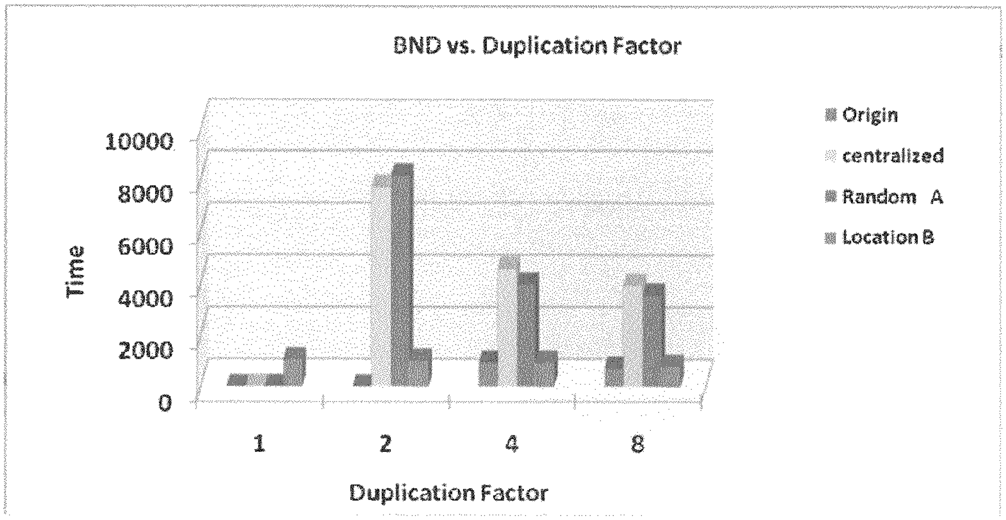
BND vs. Duplication Factor
10000
8000
6000
4000
2000
0
Time
1
2
4
8
Duplication Factor
Origin
centralized
Random A
Location B

Fig. 53

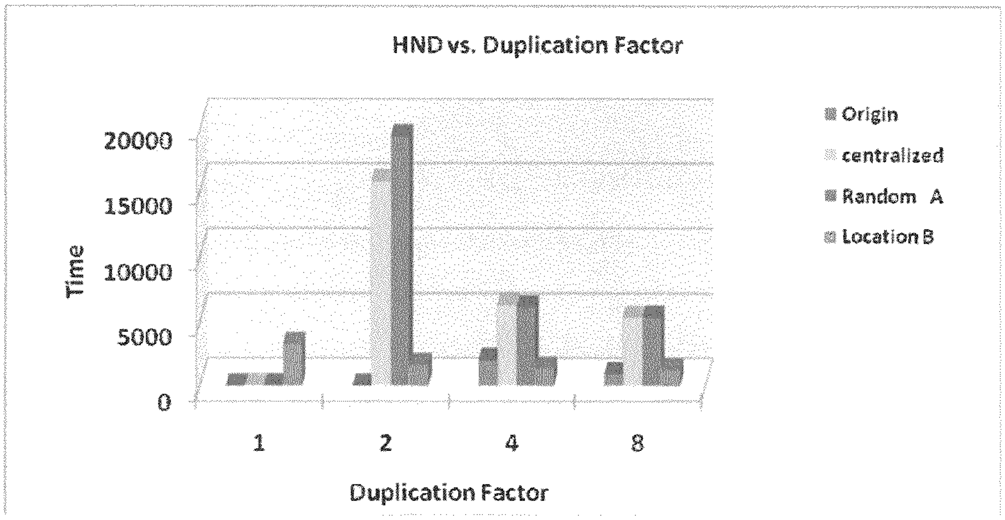
HND vs. Duplication Factor
20000
15000
10000
5000
0
Time
1
2
4
8
Duplication Factor
Origin
centralized
Random A
Location B

Fig. 54

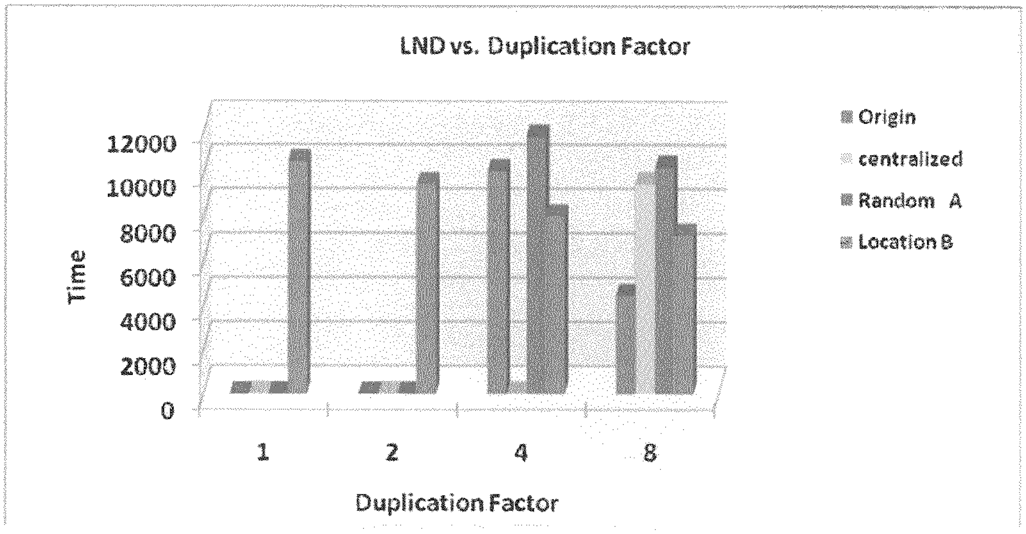
LND vs. Duplication Factor
Time
12000
10000
8000
6000
4000
2000
0
1
2
4
8
Duplication Factor
Origin
centralized
Random A
Location B

Fig. 55

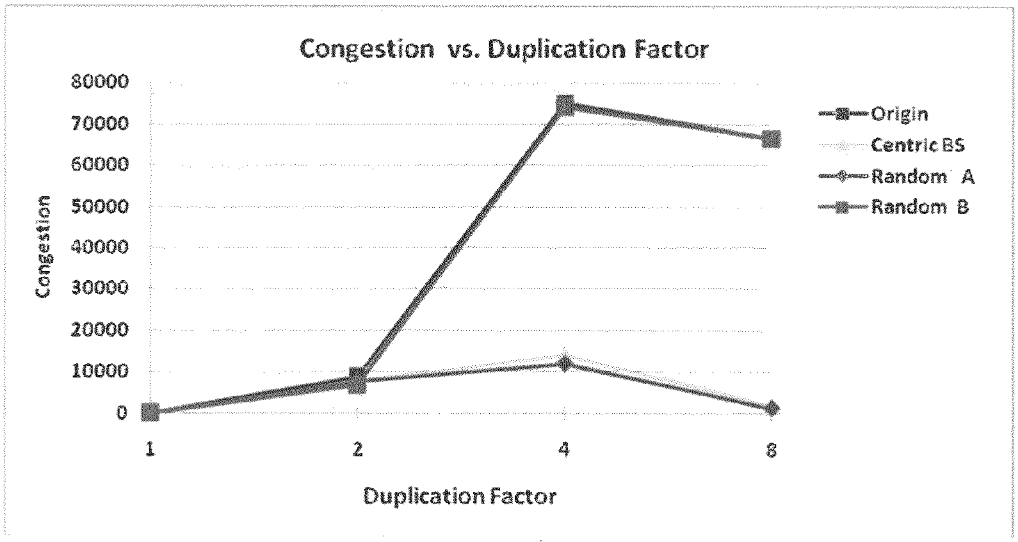
Congestion vs. Duplication Factor
Congestion
80000
70000
60000
50000
40000
30000
20000
10000
0
1
2
4
8
Duplication Factor
Origin
Centric BS
Random A
Random B

Fig. 56

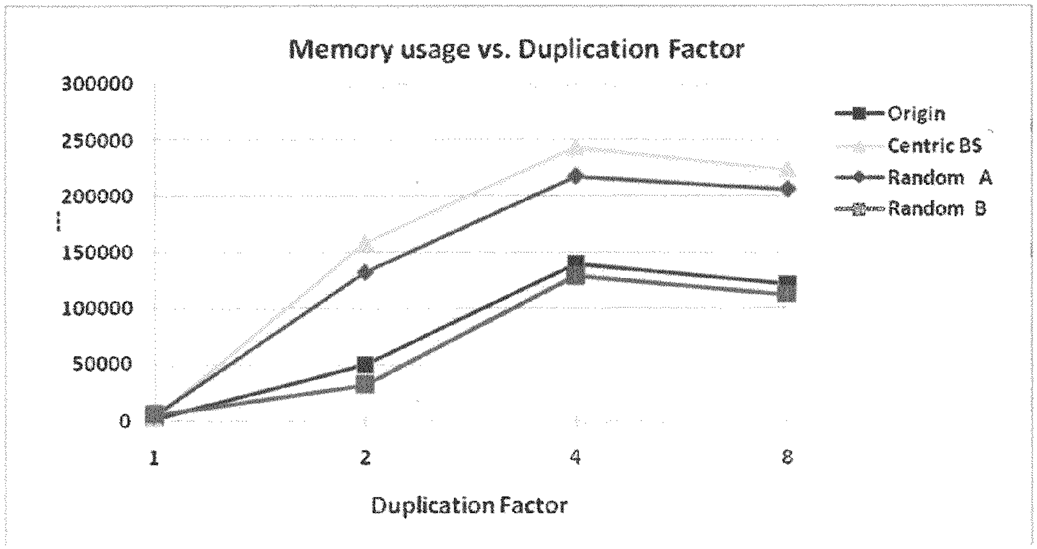
Memory usage vs. Duplication Factor
300000
250000
200000
150000
100000
50000
0
1
2
4
8
Duplication Factor
Origin
Centric BS
Random A
Random B

Fig. 57

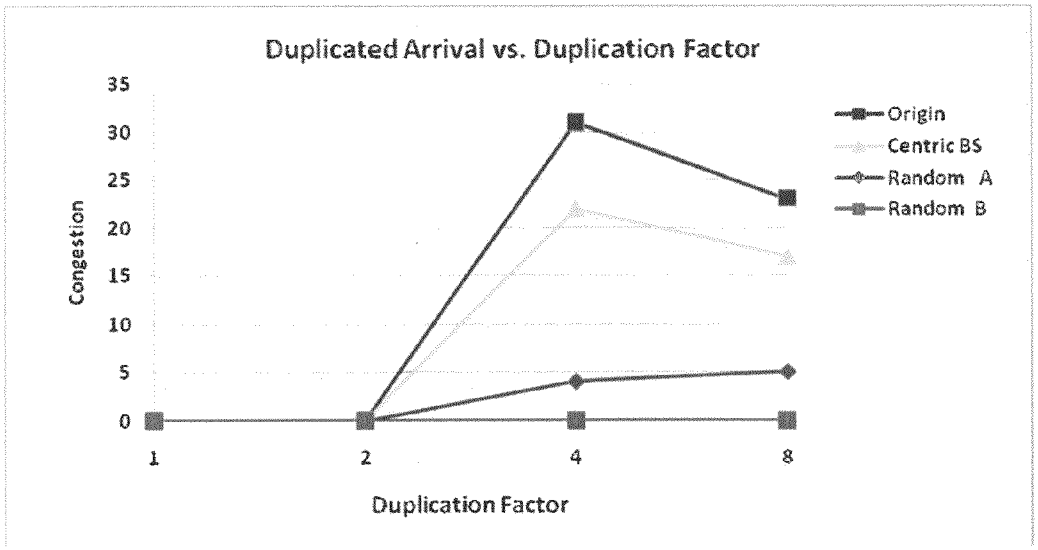
Duplicated Arrival vs. Duplication Factor
35
30
25
20
15
10
5
0
Congestion
1
2
4
8
Duplication Factor
Origin
Centric BS
Random A
Random B

Fig. 58

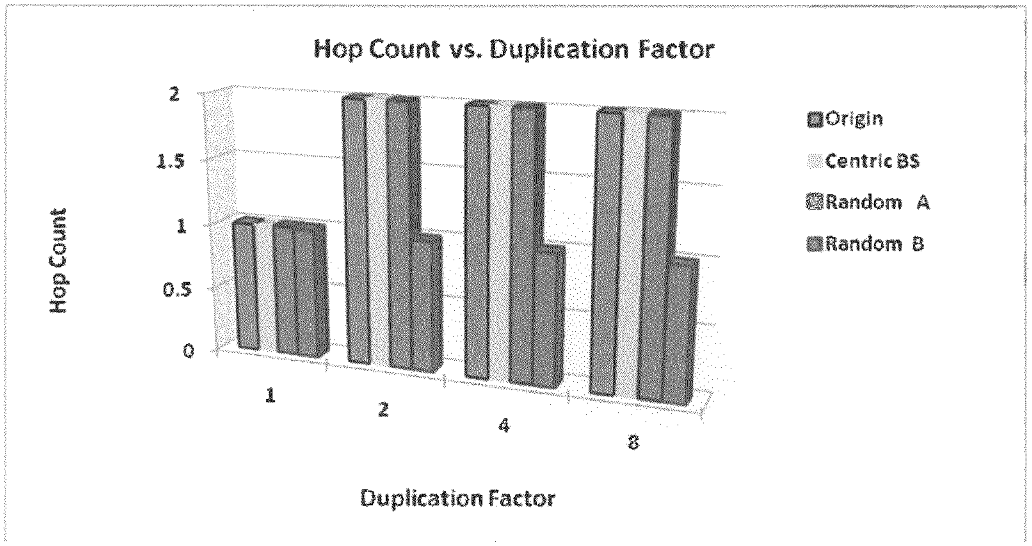
Hop Count vs. Duplication Factor
Hop Count
2
1.5
1
0.5
0
1
2
4
8
Duplication Factor
Origin
Centric BS
Random A
Random B

Fig. 59

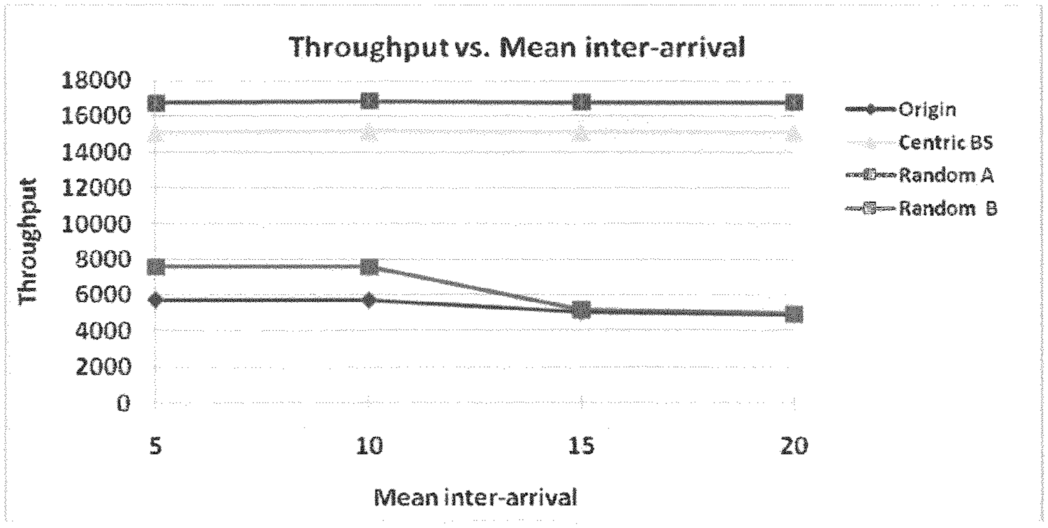
Throughput vs. Mean inter-arrival
Throughput
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Random B

Fig. 60

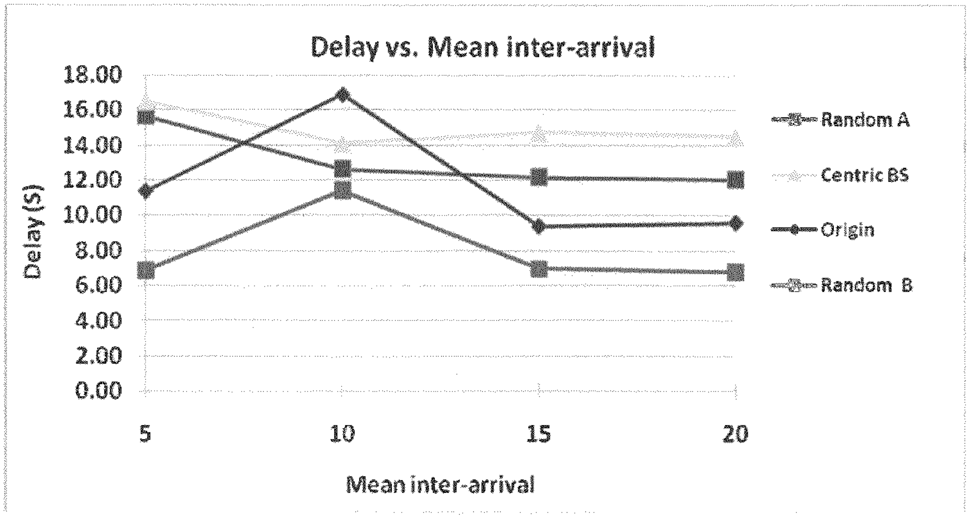
Delay vs. Mean inter-arrival
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Delay ($)
5
10
15
20
Mean inter-arrival
Random A
Centric BS
Origin
Random B

Fig. 61

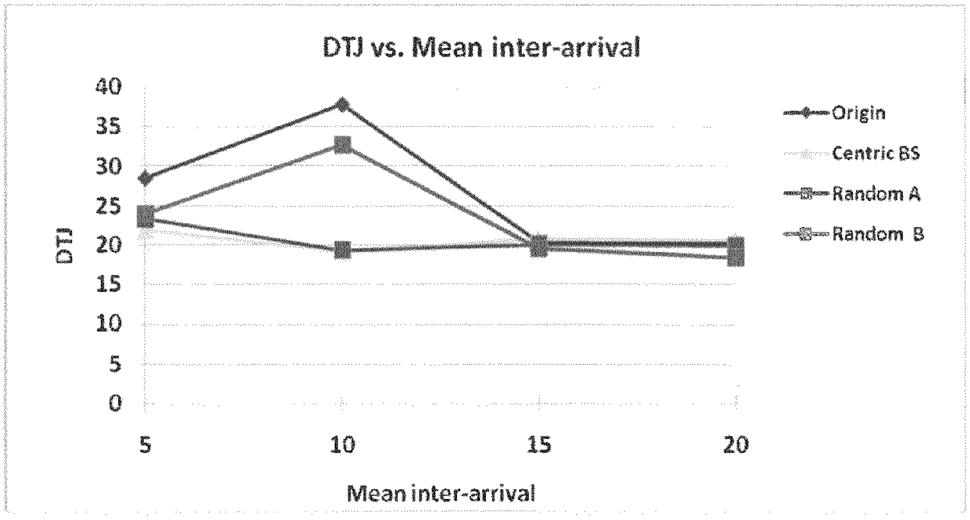
DTJ vs. Mean inter-arrival
40
35
30
25
20
15
10
5
0
DTJ
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Random B

Fig. 62

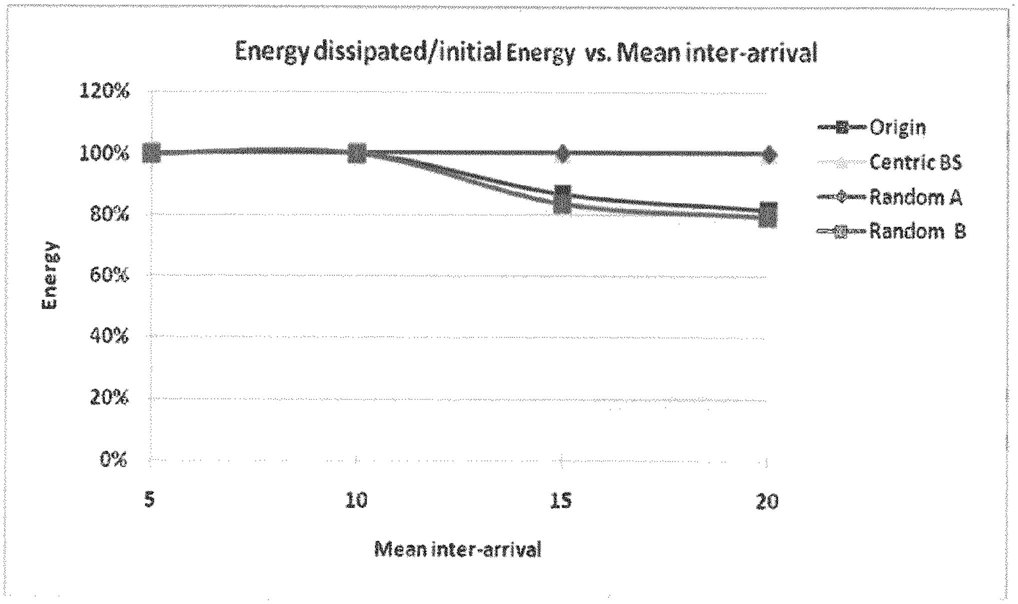
Energy dissipated/initial Energy vs. Mean inter-arrival
120%
100%
80%
60%
40%
20%
0%
Energy
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Random B

Fig. 63

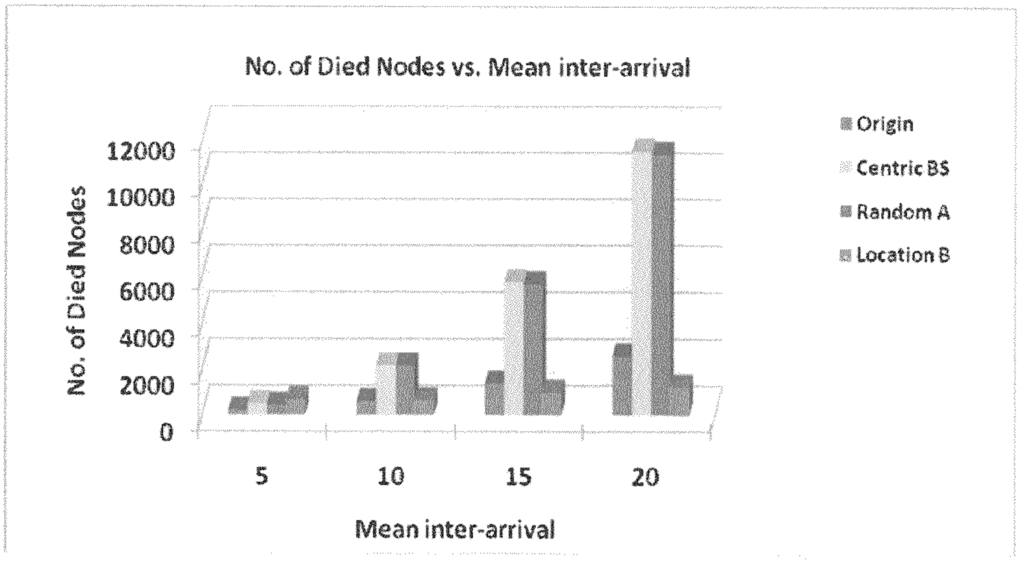
No. of Died Nodes vs. Mean inter-arrival
12000
10000
8000
6000
4000
2000
0
No. of Died Nodes
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Location B

Fig. 64

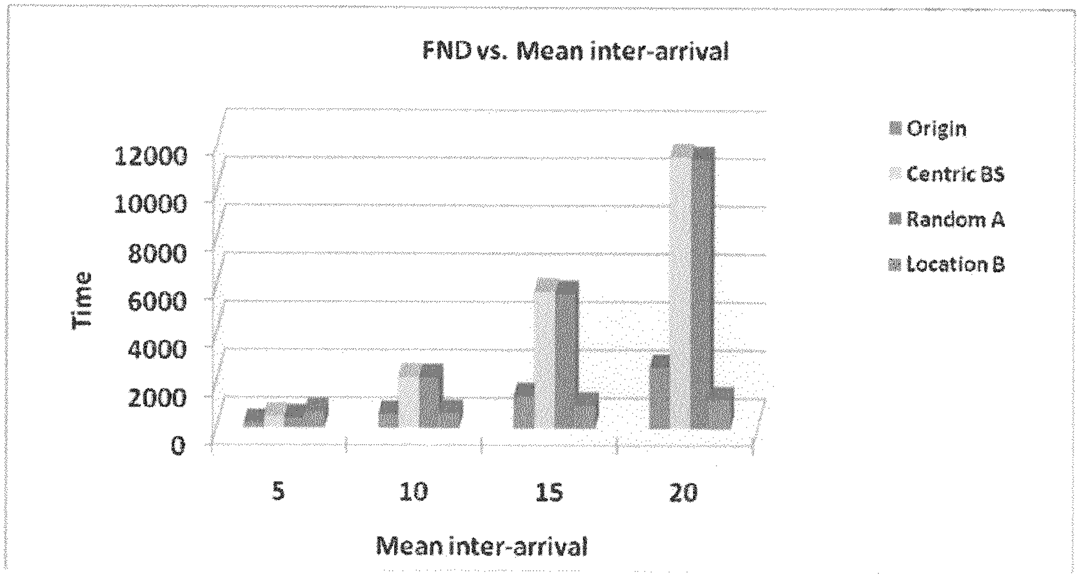
FND vs. Mean inter-arrival
Time
12000
10000
8000
6000
4000
2000
0
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Location B

Fig. 65

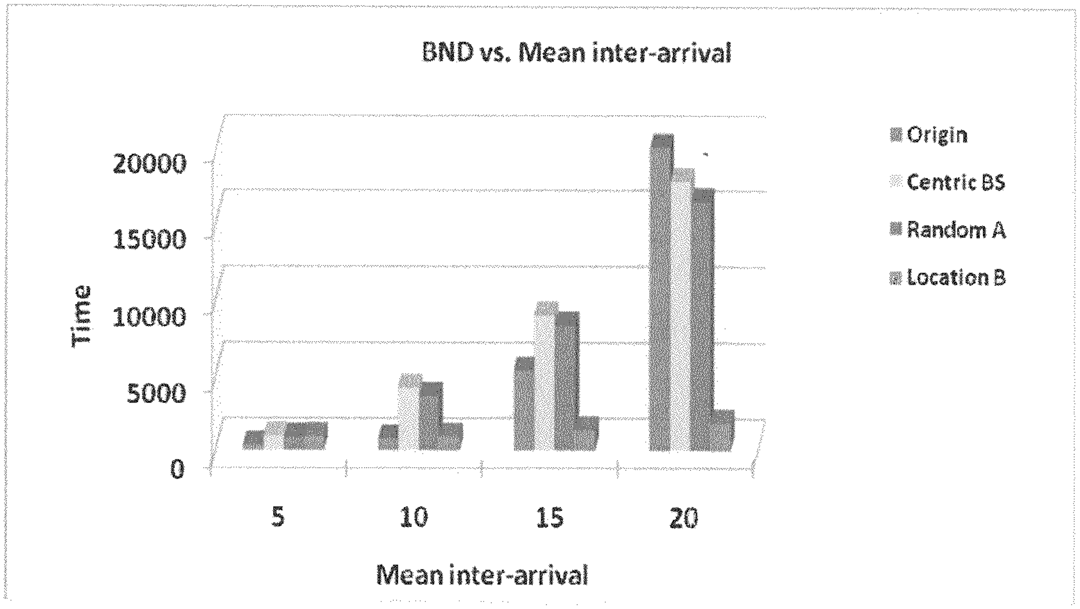
BND vs. Mean inter-arrival
Time
20000
15000
10000
5000
0
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Location B

Fig. 66

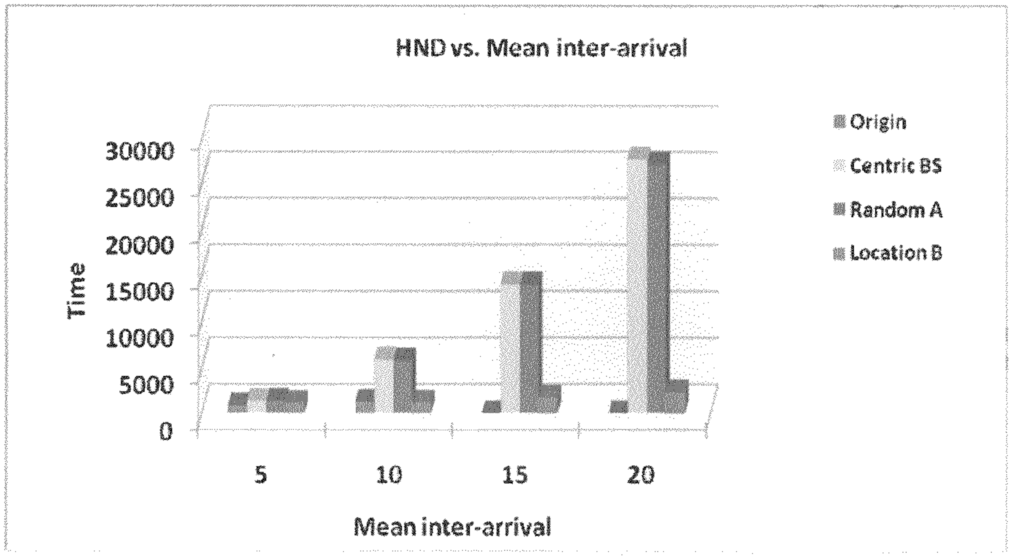
HND vs. Mean inter-arrival
Time
30000
25000
20000
15000
10000
5000
0
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Location B

Fig. 67

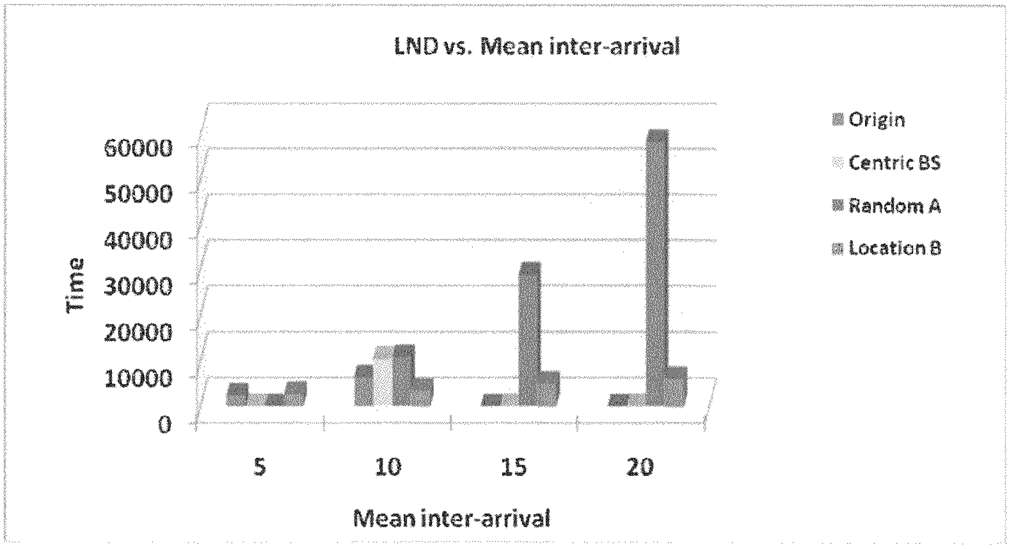
LND vs. Mean inter-arrival
Time
60000
50000
40000
30000
20000
10000
0
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Location B

Fig. 68

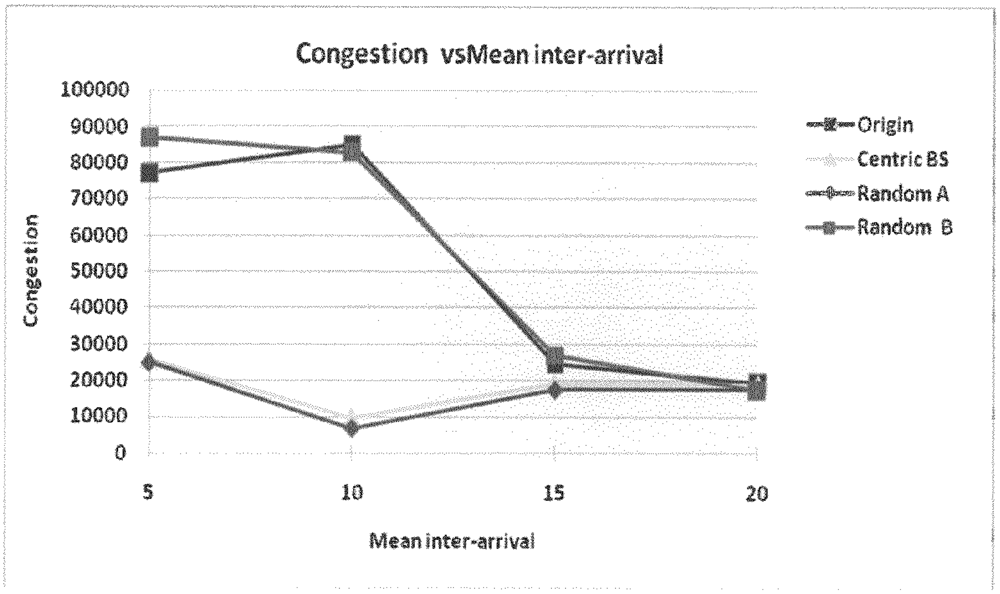
Congestion vsMean inter-arrival
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Congestion
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Random B

Fig. 69

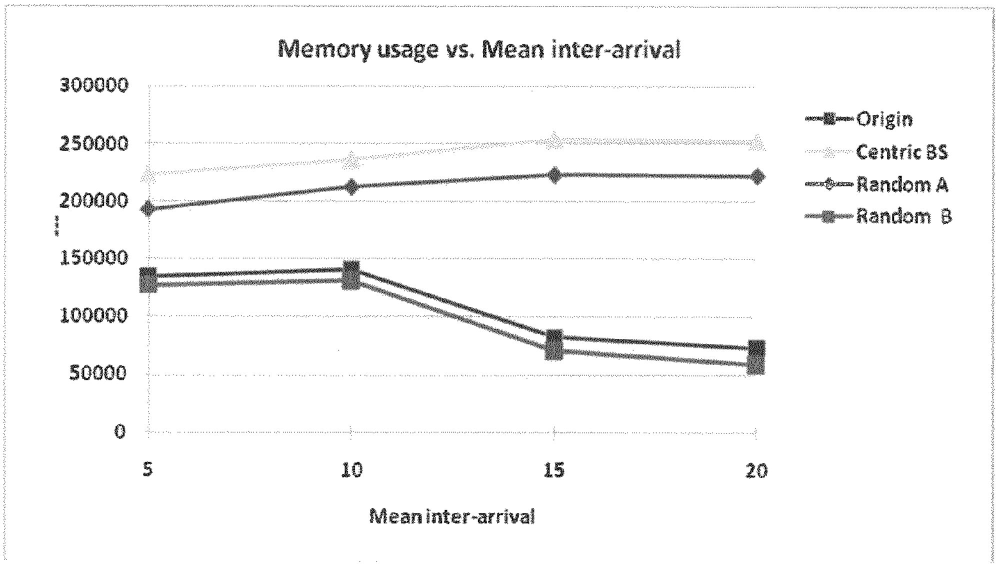
Memory usage vs. Mean inter-arrival
300000
250000
200000
150000
100000
50000
0
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Random B

Fig. 70

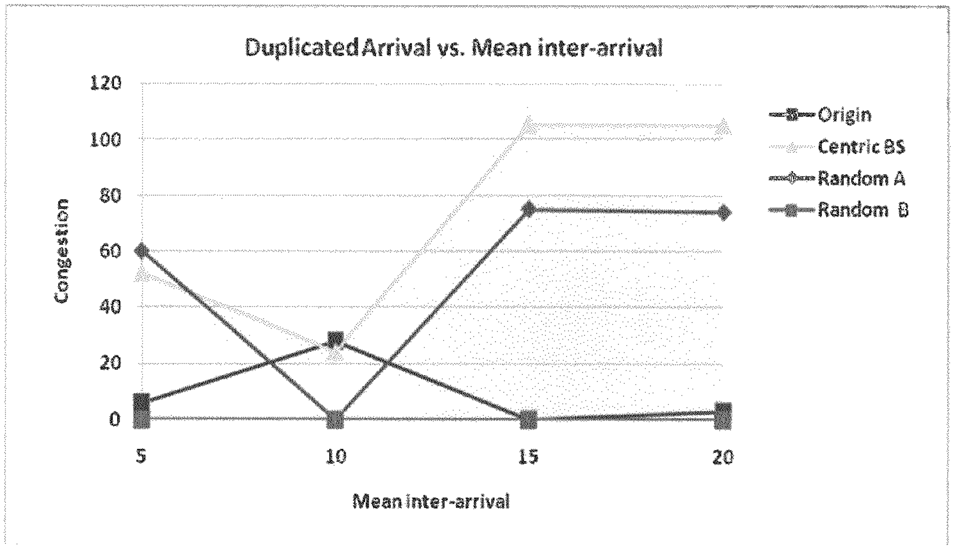
Duplicated Arrival vs. Mean inter-arrival
120
100
80
60
40
20
0
Congestion
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Random B

Fig. 71

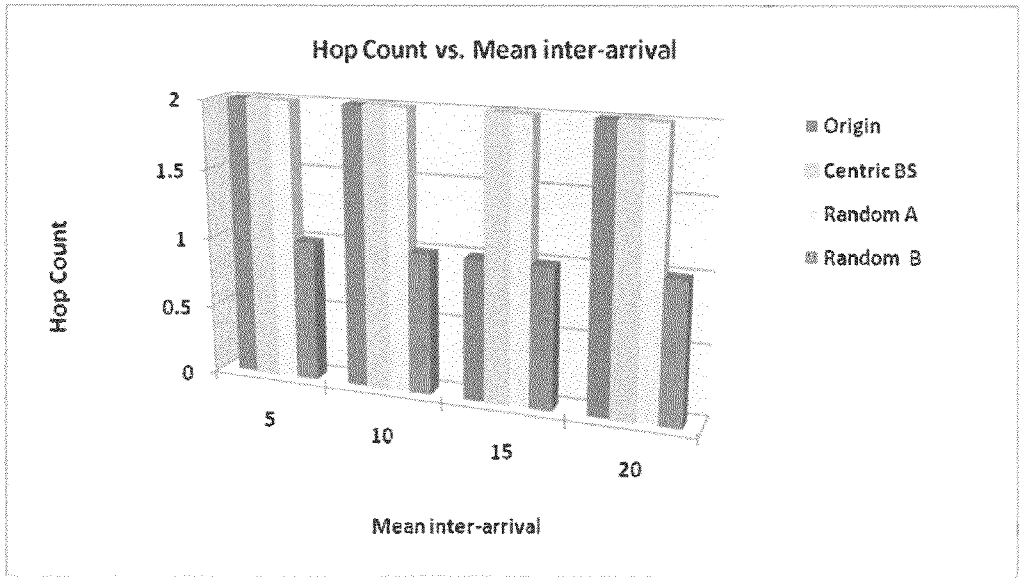
Hop Count vs. Mean inter-arrival
2
1.5
1
0.5
0
Hop Count
5
10
15
20
Mean inter-arrival
Origin
Centric BS
Random A
Random B

Fig. 72

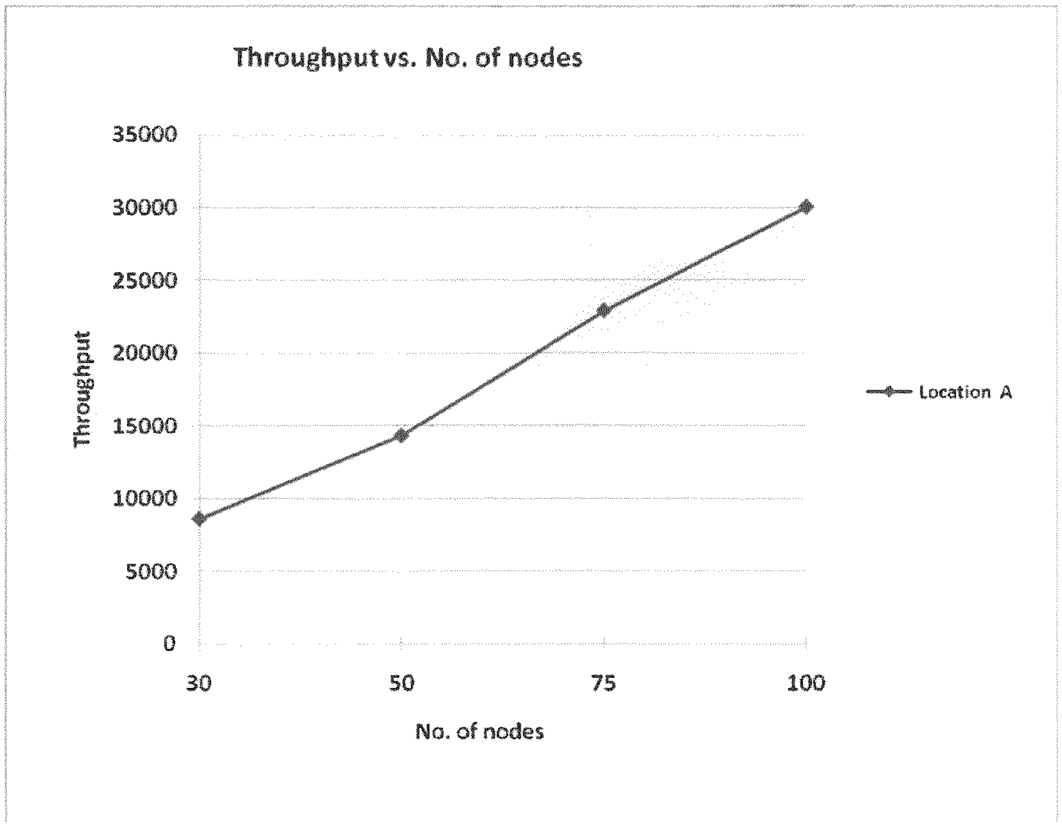
Throughput vs. No. of nodes
35000
30000
25000
20000
15000
10000
5000
0
Throughput
30
50
75
100
No. of nodes
Location A

Fig. 73 a

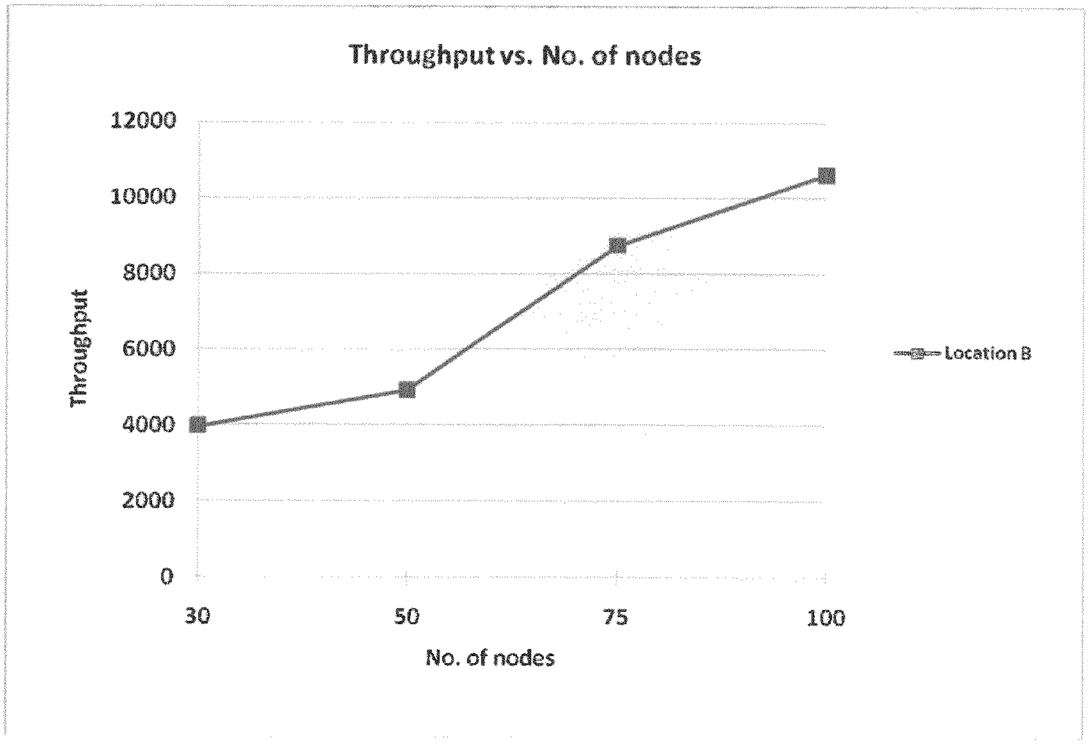
Throughput vs. No. of nodes
Throughput
12000
10000
8000
6000
4000
2000
0
30
50
75
100
No. of nodes
Location B

Fig. 73 b

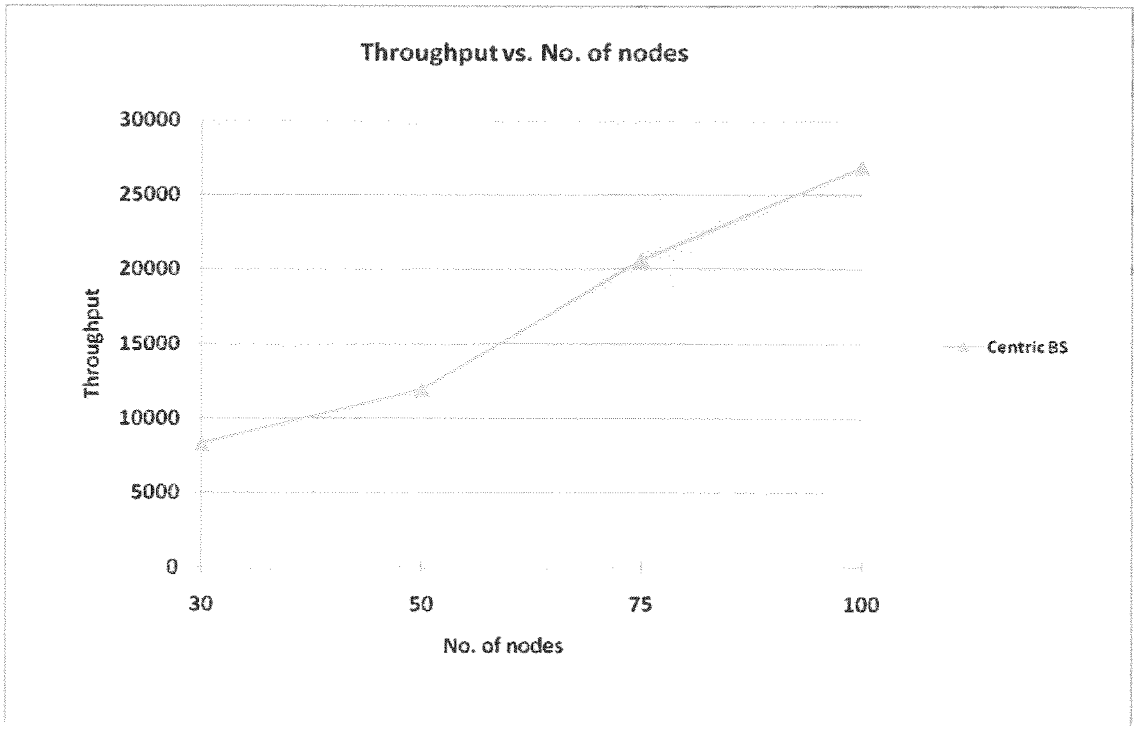
Throughput vs. No. of nodes
30000
25000
20000
15000
10000
5000
0
Throughput
30
50
75
100
No. of nodes
Centric BS

Fig. 73 c

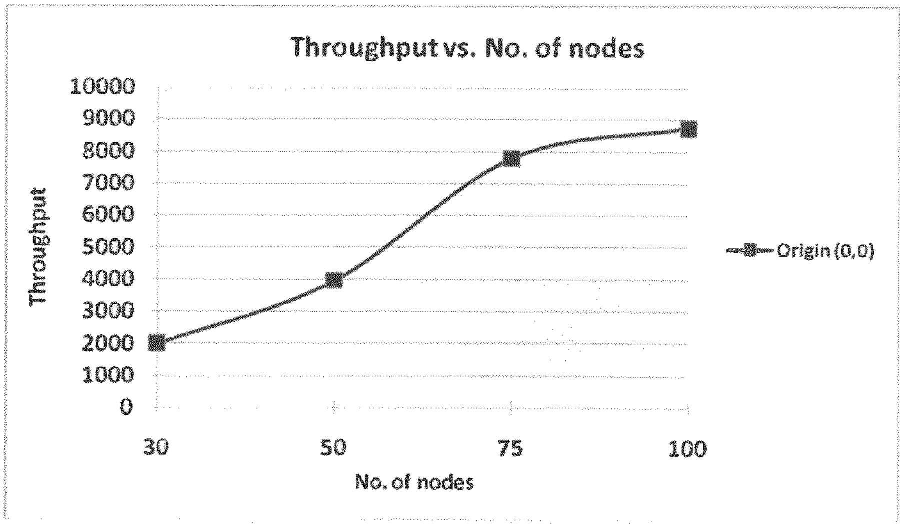

Fig73.d

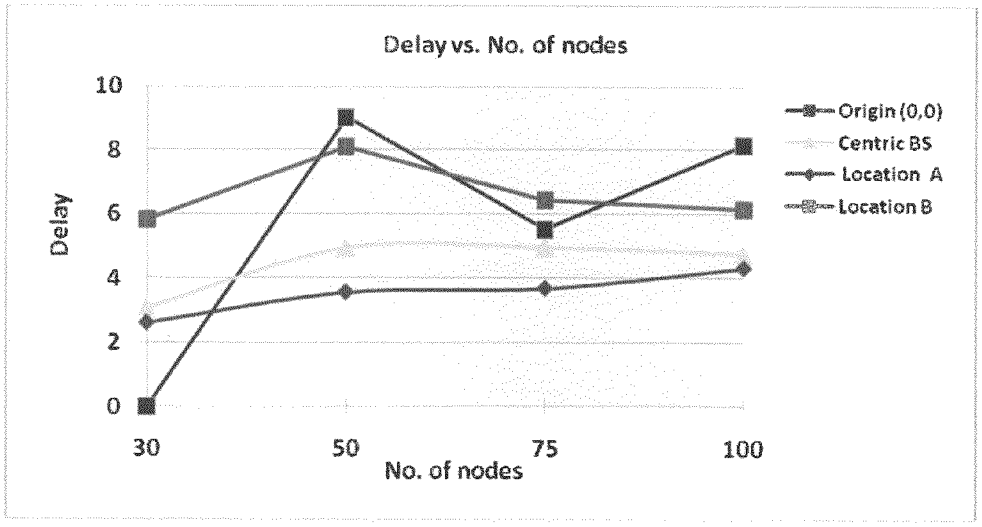

Fig74

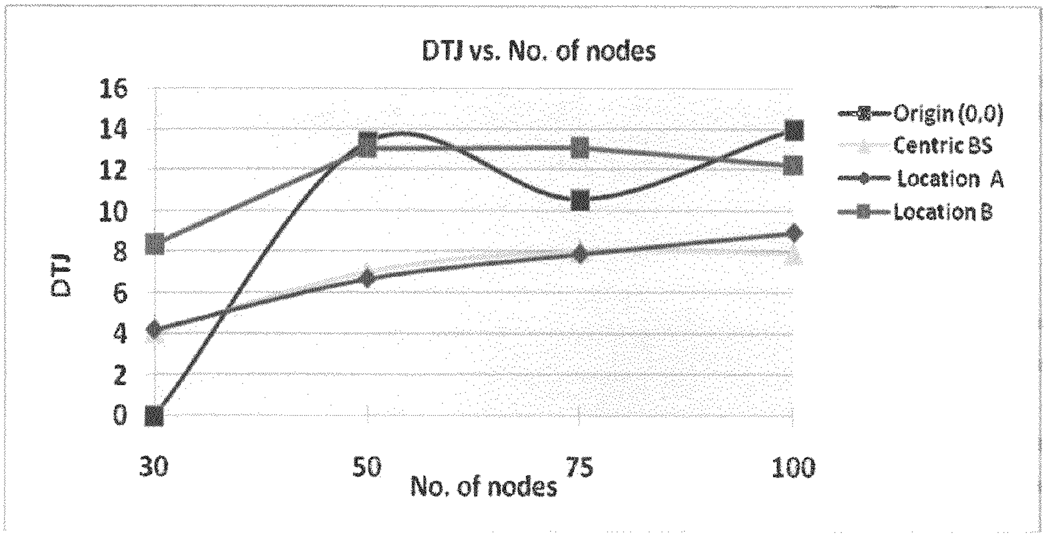
DTJ vs. No. of nodes
16
14
12
10
8
6
4
2
0
DTJ
30
50
75
100
No. of nodes
Origin (0,0)
Centric BS
Location A
Location B

Fig75

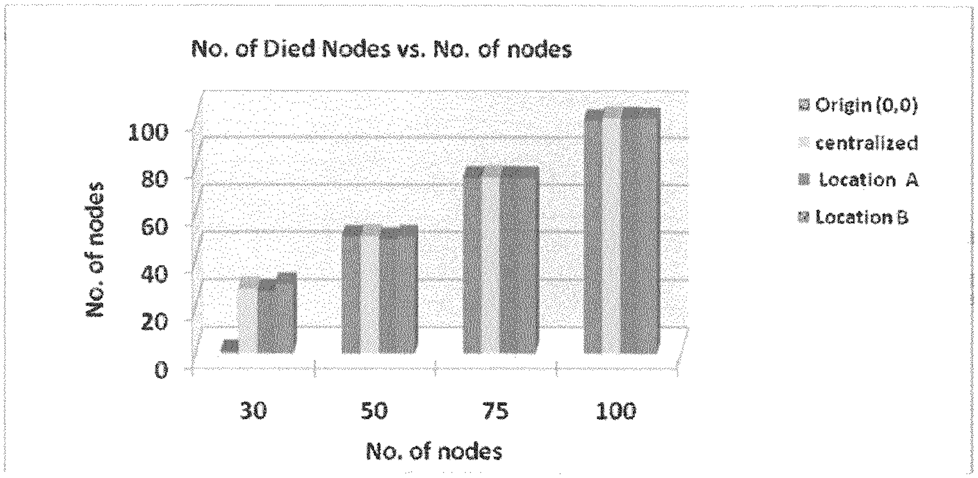
No. of Died Nodes vs. No. of nodes
100
80
60
40
20
0
No. of nodes
30
50
75
100
No. of nodes
Origin (0,0)
centralized
Location A
Location B

Fig. 76

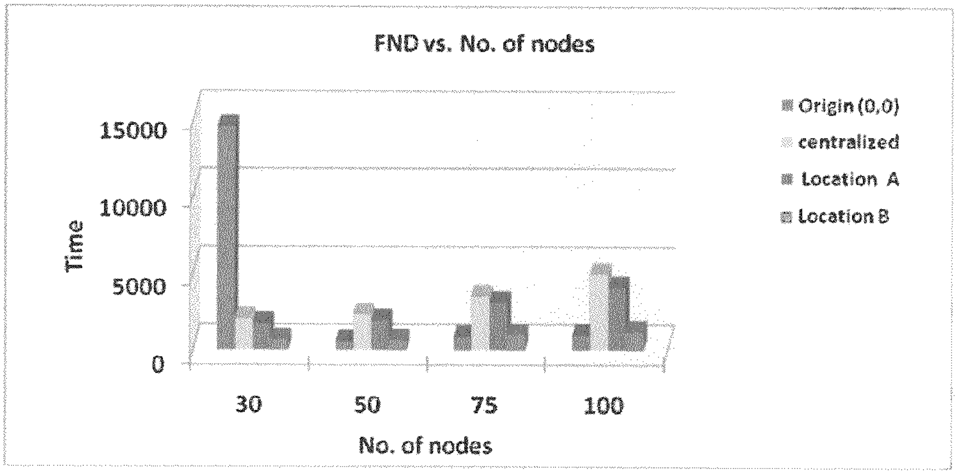
FND vs. No. of nodes
Time
15000
10000
5000
0
30
50
75
100
No. of nodes
Origin (0,0)
centralized
Location A
Location B

Fig. 77

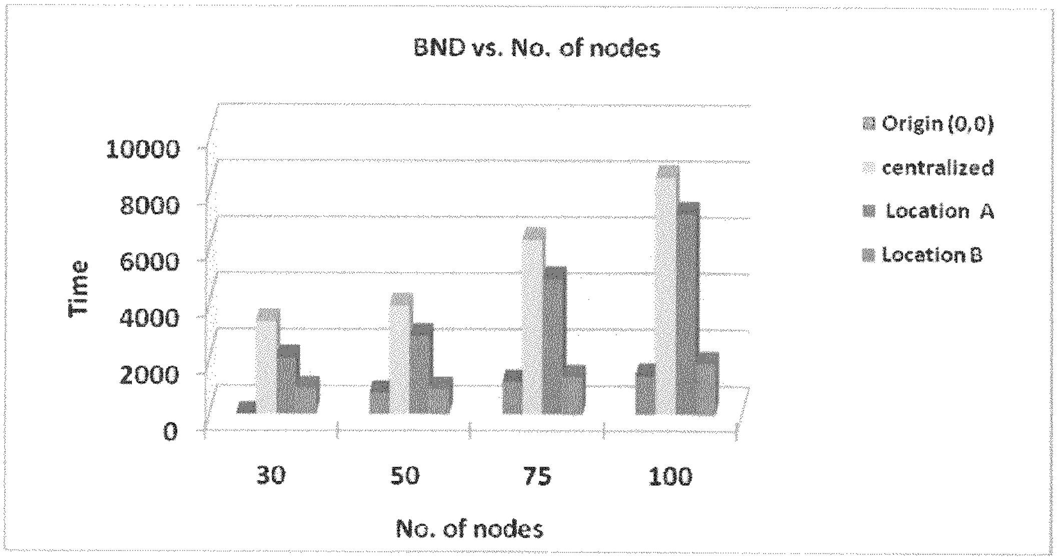
BND vs. No. of nodes
Time
10000
8000
6000
4000
2000
0
30
50
75
100
No. of nodes
Origin (0,0)
centralized
Location A
Location B

Fig. 78

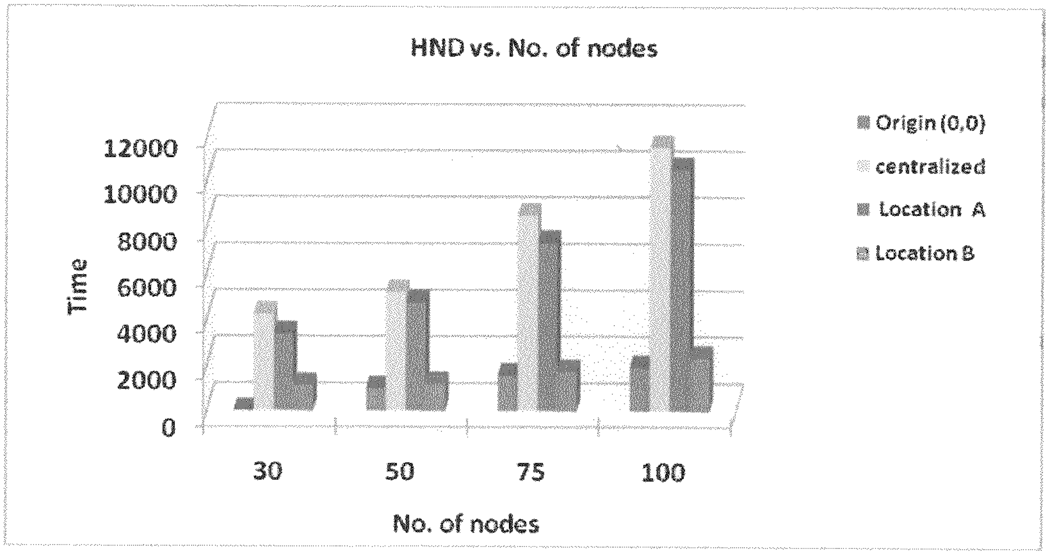
HND vs. No. of nodes
Time
12000
10000
8000
6000
4000
2000
0
30
50
75
100
No. of nodes
Origin (0,0)
centralized
Location A
Location B

Fig. 79

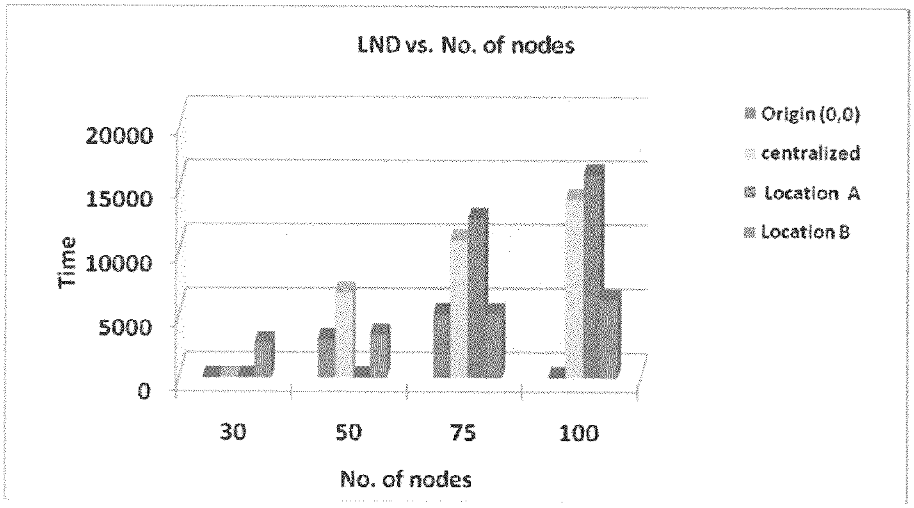
LND vs. No. of nodes
Time
20000
15000
10000
5000
0
30
50
75
100
No. of nodes
Origin (0,0)
centralized
Location A
Location B

Fig. 80

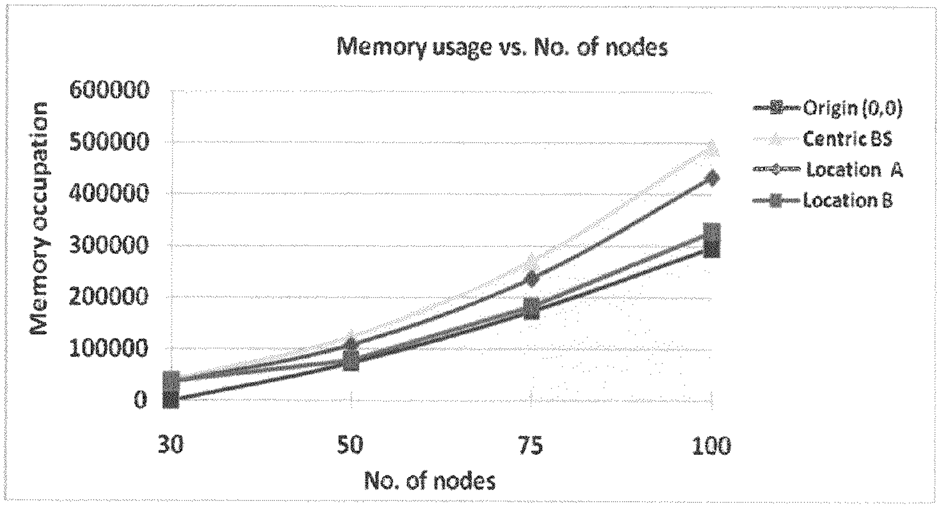
Memory usage vs. No. of nodes
Memory occupation
600000
500000
400000
300000
200000
100000
0
30
50
75
100
No. of nodes
Origin (0,0)
Centric BS
Location A
Location B

Fig. 81

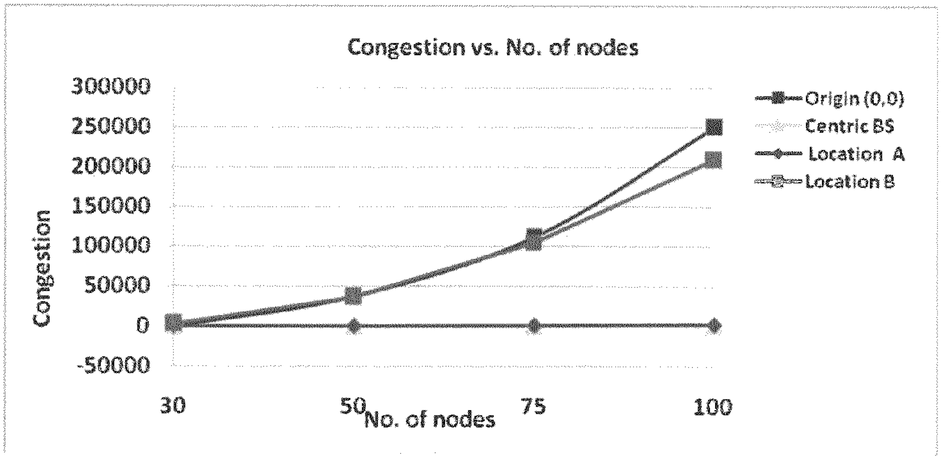
Congestion vs. No. of nodes
Congestion
300000
250000
200000
150000
100000
50000
0
-50000
30
50
75
100
No. of nodes
Origin (0,0)
Centric BS
Location A
Location B

Fig. 82

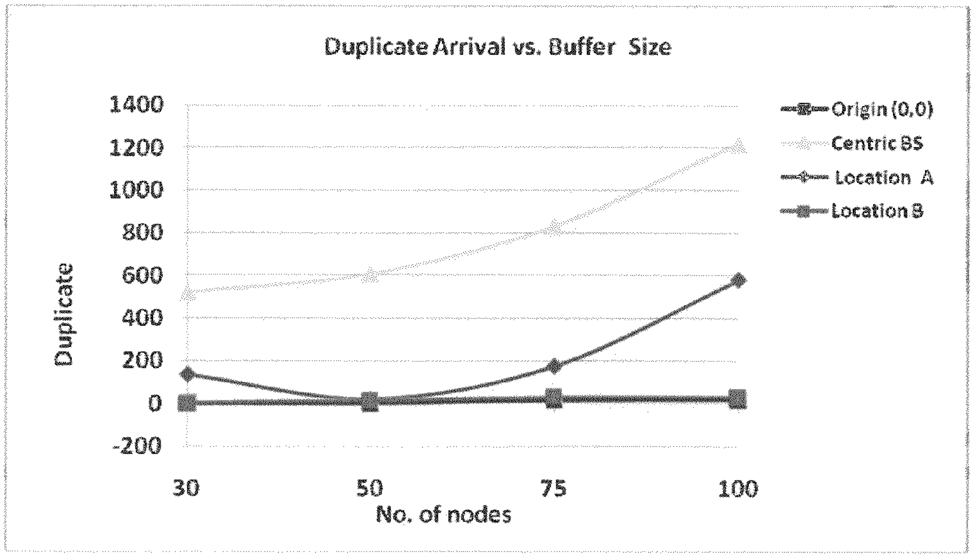
Duplicate Arrival vs. Buffer Size
1400
1200
1000
800
600
400
200
0
-200
Duplicate
30
50
75
100
No. of nodes
Origin (0,0)
Centric BS
Location A
Location B

Fig. 83

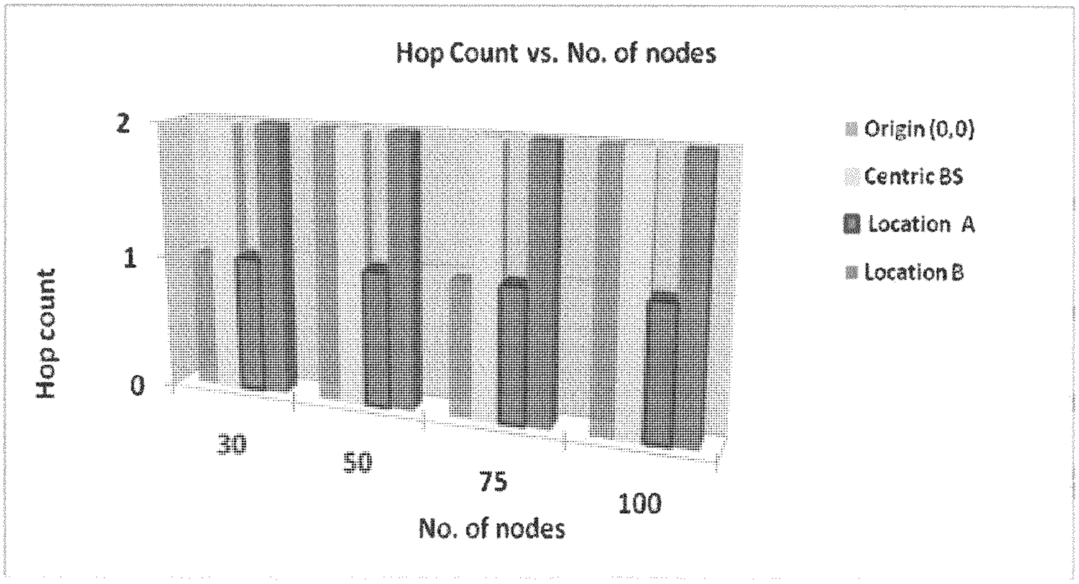
Hop Count vs. No. of nodes
2
1
0
Hop count
30
50
75
100
No. of nodes
Origin (0,0)
Centric BS
Location A
Location B

Fig. 84

COOPERATIVE PACKET ROUTING FOR WIRELESS SENSOR NETWORKS

BACKGROUND

Advances in the miniaturization of micro-electromechanical systems have led to small form-factor battery-powered sensor nodes that have sensing, communication and processing capabilities. These sensor nodes are often networked in an ad hoc manner to perform distributed sensing and information processing. Wireless sensor networks differ from other ad hoc networks by requiring a deployment phase. In general, deployment is either random or deterministic. In random deployment, sensor nodes are deployed, for example, by air-dropping them or distributing them randomly in a target environment. Using a deterministic scheme, sensors are placed at pre-determined locations.

Protocols for self-configuration of sensor nodes in a randomly-deployed wireless sensor network may not be suited for a deterministically-deployed sensor network. Similarly, node-to-node data dissemination algorithms designed for deterministic wireless sensor networks may not perform well when used in randomly-deployed sensor networks. Once deployed, however, a wireless sensor network needs very little human intervention and can generally function autonomously to provide continuous monitoring and processing capabilities. Each sensor node collects data (e.g., temperature, sound, vibration, pressure, motion, pollutants, etc.) from a monitored area. The sensing area of a sensor node is typically dependent on the type of physical sensors used by the node.

Nodes systematically route sensed data according to pre-configured communication protocols to a remote base station, where parameters characterizing the collected data are utilized for arbitrary purposes. In such scenarios, data transmission is generally node-to-node multi-hop toward the base station. Since sensor nodes are typically powered by batteries, and because route discovery and data transmission are energy-expensive operations, conserving sensor node battery power during route discovery and/or data transmission operations is a significant consideration when assessing the life of the sensor nodes in a wireless sensor network.

SUMMARY

Cooperative packet routing for wireless sensor networks is described. In one aspect, a sensor node in a wireless sensor network receives a packet from a source node or from another transient node, wherein the packet is targeted for receipt by a base station. The sensor node, responsive to receiving the packet, estimates how much operational energy remains in the sensor node. If the determined amount of energy meets a configurable threshold, the sensor node implements a set of cooperative packet routing operations for conditional re-transmission of the packet to the base station. The configurable threshold is set to ensure substantially optimal usage and lifetime of the sensor node in the wireless sensor network. The conditional re-transmission of the packet is based on a set of randomized packet re-transmission criteria.

This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the detailed description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawings will be provided by the Office upon request and payment of the necessary fee.

In the Figs., the left-most digit of a component reference number identifies the particular Fig. in which the component first appears.

FIG. **1** shows an exemplary wireless sensor network according to one embodiment.

FIG. **2** shows an exemplary wireless sensor node architecture and operating environment according to one embodiment.

FIG. **3** shows an exemplary packet for communication by a first sensor node and for receipt by one or more other sensor nodes in a wireless sensor network, according to one embodiment.

FIG. **4** shows an exemplary procedure for cooperative packet routing for wireless sensor networks according to one embodiment.

FIG. **5** shows further aspects of the exemplary procedure for cooperative packet routing for wireless sensor networks according to one embodiment.

FIG. **6** shows multiple exemplary locations for base stations according to one embodiment.

FIG. **7** shows a graph of exemplary throughput vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **8** shows an exemplary graph of delay vs. scalar factor for various locations in an exemplary sensor network.

FIG. **9** shows an exemplary graph of exemplary delay time jitter (DTJ) vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **10** shows an exemplary graph of exemplary energy dissipated and initial energy vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **11** shows an exemplary graph of number of failed nodes vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **12** shows an exemplary graph of first node to die lifetime (FND) vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **13** shows an exemplary graph of Beta of the nodes to die lifetime (BND) (e.g., Beta=20%) vs. scalar factor for various locations in an exemplary sensor network according to one embodiment. Beta is a selected percentage of the total network node population.

FIG. **14** shows an exemplary graph of half of the nodes alive lifetime (UNA) vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **15** shows an exemplary graph of last node to die lifetime (LND) vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **16** shows an exemplary graph of exemplary memory usage vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **17** shows an exemplary graph of congestion vs. exemplary scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **18** shows an exemplary graph of duplicated arrival vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **19** shows an exemplary graph of hop count vs. scalar factor for various locations in an exemplary sensor network according to one embodiment.

FIG. **20** shows an exemplary graph of throughput vs. D_{max} according to one embodiment.

FIG. **21** shows an exemplary graph of delay vs. D_{max} according to one embodiment.

FIG. **22** shows an exemplary graph of DTJ vs. D_{max} according to one embodiment.

FIG. **23** shows an exemplary graph of energy dissipated/initial energy vs. D_{max} according to one embodiment.

FIG. **24** shows an exemplary graph of the number of failed nodes vs. D_{max} according to one embodiment.

FIG. **25** shows an exemplary graph of FND vs. D_{max} according to one embodiment.

FIG. **26** shows an exemplary graph of BND vs. D_{max} according to one embodiment.

FIG. **27** shows an exemplary graph of HND vs. D_{max} according to one embodiment.

FIG. **28** shows an exemplary graph of LND vs. D_{max} according to one embodiment.

FIG. **29** shows an exemplary graph of congestion vs. D_{max} according to one embodiment.

FIG. **30** shows an exemplary graph of memory usage vs. D_{max} according to one embodiment.

FIG. **31** shows an exemplary graph of duplicated arrival vs. D_{max} according to one embodiment.

FIG. **32** shows an exemplary graph of hop count vs. D_{max} according to one embodiment.

FIGS. **33-35** show recitative graphs of throughput vs. buffer size at a centric base station, at location A, and at location B, respectively, according to one embodiment.

FIG. **36** shows an exemplary graph of delay vs. buffer size according to one embodiment.

FIG. **37** shows an exemplary graph of DTJ vs. buffer size according to one embodiment.

FIG. **38** shows an exemplary graph of energy dissipated/initial energy vs. buffer size according to one embodiment.

FIG. **39** shows an exemplary graph of number of failed nodes vs. buffer size according to one embodiment.

FIG. **40** shows an exemplary graph of FND vs. buffer size according to one embodiment.

FIG. **41** shows an exemplary graph of BND vs. buffer size according to one embodiment.

FIG. **42** shows an exemplary graph of HND vs. buffer size according to one embodiment.

FIG. **43** shows an exemplary graph of LND vs. buffer size according to one embodiment.

FIG. **44** shows an exemplary graph of congestion vs. buffer size according to one embodiment.

FIG. **45** shows an exemplary graph of memory usage vs. buffer size according to one embodiment.

FIG. **46** shows an exemplary graph of duplicated arrival vs. buffer size according to one embodiment.

FIG. **47** shows an exemplary graph of throughput vs. duplication factor according to one embodiment.

FIG. **48** shows an exemplary graph of delay vs. duplication factor according to one embodiment.

FIG. **49** shows an exemplary graph of DTJ vs. duplication factor according to one embodiment.

FIG. **50** shows an exemplary graph of energy dissipated/initial energy vs. duplication factor according to one embodiment.

FIG. **51** shows an exemplary graph of number of failed nodes vs. duplication factor according to one embodiment.

FIG. **52** shows an exemplary graph of FND vs. duplication factor according to one embodiment.

FIG. **53** shows an exemplary graph of BND vs. duplication factor according to one embodiment.

FIG. **54** shows an exemplary graph of HND vs. duplication factor according to one embodiment.

FIG. **55** shows an exemplary graph of LND vs. duplication factor according to one embodiment.

FIG. **56** shows an exemplary graph of congestion vs. duplication factor according to one embodiment.

FIG. **57** shows an exemplary graph of memory usage vs. duplication factor according to one embodiment.

FIG. **58** shows an exemplary graph of duplicated arrival vs. duplication factor according to one embodiment.

FIG. **59** shows an exemplary graph of hop count vs. duplication factor according to one embodiment.

FIG. **60** shows an exemplary graph of throughput vs. mean inter-arrival time according to one embodiment.

FIG. **61** shows an exemplary graph of delay vs. mean inter-arrival time according to one embodiment.

FIG. **62** shows an exemplary graph of DTJ vs. mean inter-arrival time according to one embodiment.

FIG. **63** shows an exemplary graph of energy dissipated/initial energy vs. mean inter-arrival time according to one embodiment.

FIG. **64** shows an exemplary graph of number of failed nodes vs. mean inter-arrival time according to one embodiment.

FIG. **65** shows an exemplary graph of FND vs. mean inter-arrival time according to one embodiment.

FIG. **66** shows an exemplary graph of BND vs. mean inter-arrival time according to one embodiment.

FIG. **67** shows an exemplary graph of HND vs. mean inter-arrival time according to one embodiment.

FIG. **68** shows an exemplary graph of LND vs. mean inter-arrival time according to one embodiment.

FIG. **69** shows an exemplary graph of congestion vs. mean inter-arrival time according to one embodiment.

FIG. **70** shows an exemplary graph of memory usage vs. mean inter-arrival time according to one embodiment.

FIG. **71** shows an exemplary graph of duplicated arrival vs. mean inter-arrival time according to one embodiment.

FIG. **72** shows an exemplary graph of hop count vs. mean inter-arrival time according to one embodiment.

FIG. **73***a-d* shows an exemplary graph of throughput vs. number of nodes according to one embodiment.

FIG. **74** shows an exemplary graph of delay vs. number of nodes according to one embodiment.

FIG. **75** shows an exemplary graph of DTJ vs. number of nodes according to one embodiment.

FIG. **76** shows an exemplary graph of number of failed nodes vs. number of nodes according to one embodiment.

FIG. **77** shows an exemplary graph of FND vs. number of nodes according to one embodiment.

FIG. **78** shows an exemplary graph of BND vs. number of nodes according to one embodiment.

FIG. **79** shows an exemplary graph of HND vs. number of nodes according to one embodiment.

FIG. **80** shows an exemplary graph of LND vs. number of nodes according to one embodiment.

FIG. **81** shows an exemplary graph of memory usage vs. number of nodes according to one embodiment.

FIG. **82** shows an exemplary graph of congestion vs. number of nodes according to one embodiment.

FIG. **83** shows an exemplary graph of duplicated arrival vs. number of nodes according to one embodiment.

FIG. **84** shows an exemplary graph of hop count vs. number of nodes according to one embodiment.

DETAILED DESCRIPTION

Overview

Sensor nodes in wireless sensor networks are prone to failure. This may be due to a variety of reasons. Loss of battery power, for example, may lead to failure of the sensor nodes. Thus, a relevant consideration in a wireless sensor network is the amount of energy and storage required for a sensor node to implement sensing, computation, and communication operations. Due to a sensor node's limited processing, memory, and power resources, standard packet routing methodologies developed for the Internet and mobile ad hoc networks typically cannot be directly applied to sensor networks. Furthermore, radio communication typically costs more in terms of energy, as compared to computation costs in a sensor node. Systems and methods for cooperative energy efficient packet routing (CEER) among sensor nodes in a wireless sensor network address these limitations of conventional wireless sensor networks.

More particularly, systems and methods for CEER, as described below in reference to FIGS. **1** through **84**, provide an energy efficient wireless sensor node communication protocol that:

- Eliminates sensor node route discovery and reconfiguration operations (e.g., cluster head selection, routing table updates, etc.);
- Utilizes minimal control messages (e.g., only base station acknowledgments);
- Substantially reduces or avoids redundant message transmission and duplicated arrival by delaying transmission to a variable amount of time relevant to node address and an arbitrary scalar factor;
- Manages congestion and node memory utilization associated with inappropriate message storage and/or packet transmission using duplication factor and base station acknowledgments;
- Accounts for randomization at different stages of deployment of the sensor array (e.g., at sensor node deployment, message origin and arrival time, and adjustment to base station location) and provides a robust system that can function efficiently and effectively in a variety of deployment schemes.
- Message Origin: Random numbers generating software is used to decide which node will generate the next message. The generated randomness comes from atmospheric noise, which for many purposes is better than the pseudo-random number algorithms typically used in computer programs.
- Message Arrival Time: In the traffic model, the arrival process of a new message is characterized by Poisson process, which is a stochastic time process that is used for modeling random events in time that occur to a large extent independent of one another.
- Adjustment to Base Station Location: To evaluate the efficiency of CEER, a sample number (e.g., four) of different locations for the base station are used. In this implementation such locations are: at the origin of network map (x=0, y=0), center of network map (x=25, y=25), and two random locations (A and B). At location A, the base station is randomly placed approximately at the middle of a deployment area with a very high nodes density. At location B, the base station is also randomly placed at the middle of a deployment area with low node density.
- Node Deployment: Ns-2 is a discrete event simulator targeted at networking research. Ns provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks. In this exemplary implementation, network simulator-2 (Ns-2) was used to generate a random network topology.

Using CEER, wireless sensor network sensor nodes cooperate in delivering sensed data to a base station, in part by controlling data packet re-transmission through an address-based timer. Moreover, a sensor node that implements CEER of packets achieves overhead reduction by controlling various parameters that affect energy dissipation.

These and other aspects of the systems and methods for cooperative energy efficient packet routing in wireless sensor networks are now described in greater detail.

An Exemplary System

Although not required, systems and methods for cooperative packet routing for wireless sensor networks are described in the general context of computer program instructions executed by one or more computing devices. Computing devices typically include one or more processors coupled to data storage for computer program modules and data. Such program modules generally include computer program instructions such as routines, programs, objects, components, etc., for execution by a processor to perform particular tasks, utilize data, data structures, and/or implement particular abstract data types. While the systems and methods are described in the foregoing context, acts and operations described hereinafter may also be implemented in hardware.

FIG. **1** shows an exemplary wireless sensor network **100** with sensor nodes **102** (e.g., **102-1** through **102**-N, and including a base station ("base station") **202**), according to one embodiment. Sensor nodes **102** within wireless sensor network **100** are randomly deployed. The network topology of FIG. **1** is only one example of an exemplary network topology. For example, although this particular example shows base station **202** located on the perimeter of the sensor node topology, in a variable node such as a topology layout, the base station **104** may be centrally located, on a different perimeter, and/or so on.

FIG. **2** shows an exemplary wireless sensor node according to one embodiment. For purposes of exemplary reference and description, the first numeral of a component reference number in a Fig. is indicative of the particular Fig. where the component was first introduced. For example, referring to FIG. **2**, the first numeral of reference number **102-1** is a "1", indicating that sensor node **102-1** was first introduced in the description of FIG. **1**. Referring to FIG. **2**, in this implementation, a sensor node **102** (a respective sensor node **102-1** through **102**-N) is a small form-factor device, characterized by limited battery power and a limited amount of memory. A sensor node **102** relies on wireless channels for receiving and transmitting data respectively from/to other nodes **102**. For example, each sensor node **102** (e.g., node **102-1**) includes, for example, power supply **202**. In one implementation, power supply **202** is supported by power scavenging units such as solar cells. Power supply **202** is operatively coupled to a processor **204** (e.g., a central processing unit (CPU)), which in turn is operatively coupled to sensor **206** for collecting and processing data from environment **208**, and transceiver **210** for communication with other sensor nodes **102**.

In one implementation, sensor **206** includes respective sub-units of sensors and analog-to-digital converters (ADCs). In this scenario, analog signals produced by sensor **206** based on detected phenomena are converted to digital signals by an ADC and then fed into processing unit **204**. The transceiver **210** connects the corresponding sensor node **102** to at least a subset of other nodes **102** and/or base station **104**.

Each sensor node **102** includes computer-readable memory ("memory") **212** comprising computer-program instructions implemented as program modules executable by processor **204**. The computer program instructions, when executed by the processor, direct the sensor node **102** to collaborate with the other sensor nodes to implement sensing and data communication tasks. For example, responsive to a node **102** sensing a set of information (i.e., sensed data **214** such as temperature, sound, vibration, pressure, motion, pollutants, and/or so on) from environment **208**, or responsive to the sensor node receiving such information from another sensor node **102**, the computer program instructions direct the sensor node to communicate the sensed information in a CEER packet **216** to base station **104**, possibly via other sensor node(s) **102**, using CEER.

In the random node distribution environment of wireless sensor network **100**, receipt by another sensor node **102** of a transmitted packet **216** (the "message arrival process") is characterized by Poisson process, which is a stochastic process time used for modeling random events in time that occur to a large extent independent of one another. In system **100**, base station **104** (base station) sends an acknowledgment for every received packet **216**. Transmissions from the base station **104** can be received by all sensor nodes **102**. Such acknowledgments include, for example, information for controlling both sensor node message transmission and storage.

FIG. **3** shows an exemplary CEER packet **216** for communication by a first sensor node and for receipt by one or more other sensor nodes in a wireless sensor network according to one embodiment. For purposes of exemplary reference and description, the first numeral of a component reference number in FIG. **3** is indicative of the particular Fig. where the component was first introduced. For example, referring to FIG. **3**, the first numeral of CEER packet **216** is a "2", indicating that the CEER packet **216** was first introduced in FIG. **2**. Referring to FIG. **3**, in one implementation, CEER packet **216** includes a substantially unique identification number (ID) **302**, a data portion **304**, source node address **306**, and transient node address(es) **308**. ID **302** is represented in X bits. Up to 2^X messages can be transmitted simultaneously by a node **102** before the node refreshes its counter (ID **302**). The size of message content (data **304**) is K bits. Each node **102** also has a source node address **306**, denoted by M-bits, as well as an M-bits transient node address **308** for every transient node **102**. Also, in the exemplary implementation, an acknowledgment packet (ACK) **218** includes a source node address (M-bits), and message ID (X-bits).

When a source node **102** determines to transmit sensed data, the transmitting node generates a packet **216** with a substantially unique ID **302** and transmits the packet. If a transmitting node **102** is the original source of the data **304**, the node is operating in source-route mode. If the node is an intermediate/transient node receiving the signal of the source node and potentially resending the packet, if necessary, the node is operating in cooperative mode. The transmitting node also flags the data message for transmission by other receiving nodes **102** in either source-route mode or cooperative mode. Based on a receiving node's respective energy level, a node may not participate in data transmission. In one implementation, if a receiving node's calculated energy level is less than a predefined energy threshold (E_{min}), the receiving node will not retransmit a received data packet **216**.

In CEER, data transmission from a source node whose energy level is greater than or equal to E_{min}, can be direct to the base station **104**, if the transmission range is acceptable. Transmission of a packet **216** is cooperative as each transient sensor node **102** in N receiving the packet will implement the following operations:

Calculate the node's ID difference:$=ID_d=ID_t-ID_{s.}ID_T-ID_S$ represents the absolute value of the ID difference between 1) the address of the node that generates the message and 2) the address of the transient node that receives the message.

Start a timer counter with value ID_d*scale factor.

Listen for base station's acknowledgment (ACK), and periodically, according to a predetermined amount of time between decrements, decrement its timer.

If the transient node does not receive the base station acknowledgment before the timer counter has timed out, the transient node retransmits the received packet **216** with its particular transient node network address appended to transient node address field **308**. This process is repeated by every transient node until the respective transient node receives an ACK **218** corresponding to the transmitted packet from the base station **104**. Upon ACK reception, each receiving node **102** clears the call and resets their ID counters **302**.

Please note that in addition to functioning as a transient node **102**, sensor nodes **102** also operate respective sensor(s) **206**. Thus, a node may originate a packet **216** responsive to sensing data **214**, perform intermediate/transient node operations by transmitting a packet **216** received from a different node, and/or be simultaneously functioning as a packet originating node and a transient node.

An Exemplary Procedure

FIG. **4** shows an exemplary procedure **400** for wireless sensor node cooperative packet routing according to one implementation. For purposes of exemplary illustration and description, operations of procedure **400** are described with respect to aspects of FIGS. **1** through **3**. In the description, the left-most numeral of a component reference number indicates the particular Fig. where the component was first introduced. In this implementation, operations of procedure **400** are implemented in the system **100** by respective sensor nodes **102**.

Referring to FIG. **4**, operations of block **402** generate and transmit a packet/message for receipt by a base station or one or more transient sensor node(s) (TNs) for subsequent relay to the base station. For example, responsive to a sensor node **102-1** sensing/detecting data **214**, the sensor node generates and broadcasts a packet **216** for receipt by base station **104**. In this scenario, the original packet transmitting node **102** is the source node. At block **404**, if a transient node **102** (i.e., a respective sensor node **102-1** through **102**-N that is not the source node) receives the transmitted packet **214**, operations of procedure **400** continue at block **406**, which are described below. Otherwise, the transient node waits to receive transmitted data and/or to sense a set of information from environment **208**.

At block **406**, the transient node, having received a transmitted packet **216** from a source node **102**, determines whether the remaining power in the transient node is greater than equal to a predefined energy threshold (please see "Other Data" **220** of FIG. **2**) amount of power. Specifically, a node will not participate in data re-transmission if its current energy is less than a predefined energy threshold (E_{min}). A variety of alternative definitions may be used for E_{min}. In one embodiment, E_{min} may be the energy level necessary to perform certain predefined tasks. Such tasks may include making a certain number of outgoing transmissions, detecting sensor input for a predefined period of time, or detecting transmission input for a certain period of time. In certain alternative situations, it may be more important to keep a sensor active and sensing, instead of the node transmitting sensed data from other nodes. Furthermore, data may be lost if a sensor loses all power, so keeping power levels above a minimum level may be a necessity.

In one exemplary implementation, the energy model for ad hoc sensor node network **100** considers the amount of energy and data storage (memory) required for a node **102** to sense data **214** from environment **208** and implement CEER to send the sensed data to a base station **104**. Different assumptions about radio characteristics, including energy (E) dissipation in sensor node transmit and receive modes, will change the advantages of different data communication protocols. This implementation of CEER, for example, utilizes a radio model where the radio dissipates E_{elec}=50 nJ/bit in the transmitter or receiver circuitry (transceiver **210**). Additionally, ϵ_{amp}=100 pJ/bit/m2 for the transmitter amplifier to achieve an acceptable E_b/number to transmit a k-bit message a distance d, the radio expends:

$$E_{Tx}(k,d)=E_{elec}*k+\epsilon_{amp}*k*D_{max}, \tag{1}$$

wherein D_{max} is the maximum node transmission (T_x) distance. To receive (R_x) this message, the radio expends:

$$E_{Rx}(k)=E_{elec}*k, \tag{2}$$

If the amount of remaining power in the transient node is less than the predefined energy threshold, operations continue at block **408**, where the transient node discards the received packet. However, if the amount of remaining power in the transient node is greater than or equal to the predefined energy threshold, operations continue at block **410**. Since there may be a certain amount of redundancy in the system, it is not necessary to have every node participate in cooperative data transfer for every transmission. Certain nodes may rest during certain data cycles, for example, due to low power.

At block **410**, the packet receiving transient node **102** determines whether the packet **216** is a new packet (i.e., the packet has not been received by this particular node before). If the packet **216** is a new packet, operations of procedure **400** continue at block **402** of FIG. **5**, as illustrated by on-page reference "B." Otherwise, if the packet **216** is a duplicate packet (i.e., the transient node has received a similar packet in the past), operations of block **412** determine whether the maximum number of copies (i.e., duplicates) of the packet has been reached. The duplicate counter is utilized, for example, as a measurement device to assist in developing performance metrics of the system. In one implementation, the maximum number of copies may be set to the number of bits allocated in memory **208** for recording the occurrence of the transmission of copies. The duplication factor saves space in memory **208** by limiting long message storage, when it is likely that a received packet **216** is stored in other neighbor nodes.

If the maximum number of packet duplicates has not been reached, operations of block **414** increment the copies/duplicate counter (please see "Other Data" **220** of FIG. **2**) to indicate that another duplicate packet **216** has been received. After the operations of block **414**, operations of procedure **400** continue at block **404**, as illustrated by on-page reference "A," where a sensor node **102** waits to receive a packet **216** generated by a source node **102**. In this latter scenario, a waiting node could also become a source node, if the sensor node generates and transmits a packet **216** to other sensor nodes **102** responsive to sensing/detecting information from environment **208**.

Referring to the operations of block **412**, if it was determined that a maximum number of copies had been received by the transient node, operations of the procedure continue at block **416**. Operations of block **416** turn off the transient node timer, reset what was started by the transient node responsive to receiving the packet **216** (please see the operations of block **504** of FIG. **5**, which is described below). Operations of block **416** additionally free up the memory of a transient node by discarding the received packet (block **404**) and any stored duplicate packets. The operations of block **416** may prevent a node **102** from needlessly wasting processing energy to process the received packet when the message is likely stored in neighboring node **102**. Continuing from block **410**, if the packet is a new packet, the operations continue at block **502** of FIG. **5**, as shown by on-page reference "B."

FIG. **5** shows further exemplary operations of procedure **400** of FIG. **4** for wireless sensor node cooperative packet routing according to one implementation. For purposes of exemplary illustration and description, operations of FIG. **5** are described with respect to aspects of FIGS. **1** through **4**. In the description, the left-most numeral of a component reference number indicates the particular Fig. where the component was first introduced. Referring to FIG. **5**, operations of block **502** determine whether memory is available for storage (in memory **208** of FIG. **1**). If memory for storage of the packet is not available, operations proceed to block **408** of FIG. **4**. The operations of block **408** discard the received packet at the transient node since no memory is available to perform the data monitoring operations. The operations of the procedure then continue to monitoring for new packets.

If operations of block **502** determine that memory is available for packet **216** storage, then the procedure continues at block **504**. Operations of block **504** perform operations including, for example, calculating the difference in identifiers **302** between the sending node **102** and a transient node **102** to achieve a difference value (please see "Other Data" **220**), setting the timer to the difference value times a scale factor (please see "Other Data" **220**), and storing the packet. The scale factor value may change the operation of the wireless sensor node cooperative packet routing procedure. The selection of scale factor is dependent on the network operation. It should be set by a network administrator to achieve the required quality of service (QoS) in the application area and the permissible amount of delay to deliver the nodes data.

Operations of block **506** include waiting for an ACK **218** from the base station **104** that the packet **216** has been received. The operation waits for one unit of time and then decreases the timer by that unit of time. In block **508**, the system determines whether the ACK has been received. If the ACK has not been received, the flow continues to block **512**. The operations of block **512** include determining whether time (calculated from the difference in ID times the scalar factor in block **504**) has expired. If time has not expired, operations continue at block **506**, and the system again waits for a unit of time to expire while monitoring for the ACK. If the timer has expired (block **512**), then the operations proceed to block **514**. The operations of block **514** include appending the address of the transient node and re-transmitting the packet. The occurrence of the re-transmission step suggests that the node **102** from which the transient node received the packet is not within transmission range of the base station and/or that other transient nodes **102** receiving the packet are also not within range or have not yet re-transmitted the packet if they are in range of the base station. In any case, the packet has not yet reached the base station, and the transient node in question has waited sufficiently long for the packet to reach the base station—so the packet is retransmitted.

If in block **508** an ACK **218** has been received, then the packet **216** has been delivered to the base station **104** and it is not necessary for a node **102** to retransmit the packet. The process continues at block **510**. Since the packet has been received at the base station, the timer can be reset and portions of memory **108** comprising corresponding packets and data can be de-allocated. After packet re-transmission operations of block **514** or the reset timer and memory operations of block **410**, the procedure continues at block **404** (FIG. **4**) where the node **102** waits for a new packet **216** to be received.

Exemplary System Configuration Considerations

Various settings of the nodes of the system **100** for cooperative packet routing for wireless sensor networks may affect the performance of the system **100** in terms of message transmission time, energy consumption, and node failure time. These settings (or technical specifications) can include the above described scalar factor, D_{max}, buffer size (memory size), duplication factor, and the number of nodes used in the system. Furthermore, the system may be affected by environmental factors such as the mean inter-arrival time of packets resulting from the detection of a stimulus with a sensor.

The effects of various settings for the nodes **102** have been tested in simulation. In the simulation, inputs were designed to be realistic and suitable for both the specification sensor nodes and network functionality. The simulation was run for inputs of 40,000 simulation messages, and initial energy per node equals 2.26 e+7 nJ/bit. The nodes were given the ability to send and receive 1000 messages. However, this initial energy was very low compared to the expected amount of energy required to transmit 40,000 messages as well as the dissipation of energy resulted by receiving these messages. For this reason, it was expected that most of the nodes would fail, if not all, during the simulation run. The throughput to energy dissipation/initial energy and nodes lifetime was compared. A reasonable buffer size per node to store 20 messages was used. The transmission distance, D_{max}, that does ensure network connectivity was 10 m. The inter-arrival time was environment-dependent. It indicated traffic load carried by nodes in network. A mean inter-arrival time of 0.5 s was assumed. Duplicate factor was factor- and environment-dependent. In testing, it was basically equal to 5. A variety of scalar factor values were examined. In most runs, the value was equal to 0.5.

FIG. **6** shows an exemplary set of wireless sensor nodes (nodes **1** through **99**) and multiple exemplary locations (O—Origin, A, B, and C) for base stations according to one embodiment. This example illustrates four different locations for base station **104** (FIG. **1**). In this figure, shapes are not assigned any specific meaning. The efficiency of the system **100** considered four different exemplary locations for base station **104**—many other possible locations can be used. These locations are listed below and shown in FIG. **6**:

1) Origin O, at (0,0): in this case, the base station is placed such that it is not accessible by a substantial number of the sensor nodes. Also, node density around the base station is very low. The throughput of the system will basically depend on the lifetime of the key nodes that connect the base station with the rest of network.
2) Center, C, at (25, 25): the base station is at a focal point of the deployment area. In this case, the base station is accessible by a larger number of nodes (as compared to the above-described origin location), and the number of nodes around the base station is relatively good.
3) Two random locations:
    - A at (22.97, 31.79): the base station is randomly placed approximately in the middle of a deployment area. In this scenario, node density around the base station is highest.
    - B at (8.92, 4.57): the base station is placed at a random deployment area. In this example scenario, the node density around the base station is low.

TABLE 1

Density Of Nodes Around Base Station

Location			Number of base station's reachable nodes for a given D_{max}				
base station	X	Y	$D_{max} = 5$	$D_{max} = 10$	$D_{max} = 15$	$D_{max} = 20$	$D_{max} = 25$
O	0	0	2	7	10	10	15
C	25	25	4	18	32	60	76
A	22.97	31.8	8	20	35	54	75
B	8.92	4.57	3	9	12	17	28

FIG. **5** shows a graph of exemplary throughput vs. scalar factor for various locations in an exemplary sensor network according to an embodiment. The value of the scalar factor has a direct influence on end-to-end-packet communication delay since it is used in the described systems and methods to control a timer value (waiting period). The scalar factor has a positive effect on energy dissipation. It delays the transmission of the received message for a certain amount of time; within that time a message might be received and acknowledged by the base station which saves energy and minimizes the overhead caused by this re-transmission. It also saves energy that would be dissipated if the message is transmitted and received by neighbor nodes. On the other hand, it may have a limiting effect on memory occupation, as a message may be stored for a long time upon ACK receiving or if the timer is turned off.

Given the simulation's input of 40,000 simulation messages, a buffer size to accommodate 20 average estimated size packets, a mean inter-arrival time=0.5, an initial energy per node=101e+7, a duplicate factor=5, and D_{max}=10 m, extracted results of scalar values which were: 0, 0.1, 0.5, 1, 2, 5, and 10. Results are shown in the next four tables, FIGS. **7** to **19**, and the following Table showing exemplary performance results of varying the maximum signal receiving distance between nodes ("D_{max}") for network C and network A according to one embodiment.

	Base station Location									
	Random Location A					Centric (25, 25)				
	Dmax Value									
	5	10	15	20	25	5	10	15	20	25
Throughput	5786	16828	30010	39693	35000	2715	15147	26806	40000	40000
Delay	27.48	12.60	4.31	1.79	0.39	51.8135	14.0662	4.73355	0.986106	0.36365
Delay Time Jitter	38.18	19.30	8.97	4.12	0.77	41.9125	19.1394	7.90716	2.08838	0.796836
Total energy dissipated/ initial Energy	55%	100%	100%	89%	55%	53%	100%	100%	78%	61%
No. of Died Nodes	47	99	99	63	6	50	99	99	27	5
FND	1988.61	2094.26	4014.72	7923.31	11934.50	2012.49	2094.39	4845.97	11084.6	14720.4
BND	2586.68	3565.95	7109.00	14080.60	0.00	2518.6	4098.71	8391.61	16375.1	0
HND	4794.16	5642.78	10375.70	17877.70	0.00	3628.22	5732.47	11328.8	0	0
LND	0	10722.4	15830.9	0	0	17800.7	10208.6	13872.7	0	0
Congestion	1337	6699	1970	110	0	1453	9468	1068	169	0
Duplicated Arrival	0	0	577	1580	1810	0	24	1217	1817	1860
hop count/ message	3	2	1	1	1	5	2	2	1	1
Occupied Memory (Sum)	51307	212247	432700	500191	335598	53544	235809	492488	461485	350521

FIG. **7** shows the highest throughput for base station at (A) which has the highest nodes density around the base station. Non-zero scalars have a positive impact over throughput for all base station locations compared to zero scalar. The ongoing growth of scalar value does not deduce higher throughput. When determining scalar value, one may balance between the tendencies to save re-transmission energy, preventing overhead, required storage, and delay caused by the scalar factor. In one implementation, for example, the scalar value is between 0.1, 0.5, and 1, as it has exhibited excellent throughput, increase of storage sharing, and also generally results in less delay as compared to the use of other values for this term. Use of upper scalar values (e.g., 2, 5, and 10) reduces throughput, minimizes memory sharing, and has a very high delay. It causes large message loss due to the memory shortage as a result of the long duration of blocking but not frequency of blocking. As expected, scalar factor is directly proportional to delay and delay time jitter as shown in FIGS. **8** and **9**. Values of delay and DTJ for scalar 0.1 and 0.5 is reasonable compared to the improvement in network throughput.

It is expected that most nodes dissipate all of their respective energy and fail. Focus was given to: 1) time nodes fail, and 2) the amount of message successfully routed by the mean of this energy. FIG. **10** shows that around 100% of energy is dissipated in all four networks. The longer the amount of time that it takes nodes to fail reflects better energy efficiency and higher network functionality. A value of zero for FND, BND, HND, and LND indicates that this condition was never satisfied; i.e., if LND=0 indicates that there is at least one node that remains alive until the end of simulation.

FIGS. **11**, **12**, **13**, **14**, and **15** show a direct relationship between network live time and scalar values. It also shows that network “C” and “A” have higher measures than other networks in all FND, BND, HND, and LND. Network “C” shows better energy utilization than “A” fail time in FIGS. **13** and **15** for some scalar values due to changes in node density around the base station at each case. However, this difference is still small and ranges from zero to a few seconds. FIGS. **16**, **17**, and **18** show poor values in congestion, duplicated arrival, and memory occupation for zero scalar value. Escalating scalar value improves all of these measures. FIG. **18** shows how scalar prevents duplicated message arrival to the base station. There is a similarity in the performance between networks “A” and “C” and between networks “O” and “B”, since they have similar conditions.

FIG. **19** shows that hop count is optimized with a non-zero scalar value. The reason for this is that the amount of energy dissipated by direct re-transmission affects most of the nodes that connect network segments early. As a result, later messages will typically follow a long path to reach the base station. This shows how scalar factor affects the different performance measures. However, this effect is not linearly related in all cases. There is an optimal value for scalar factor that preserves energy and memory with minimum delay. Scalar should be within that threshold, and threshold value depends on the state of the network. To obtain this, the following proportions between scalar factor and other measures were utilized:

Scalar Factor (SF) and Throughput (Thro.)

$$\mathrm{SF} \propto \mathrm{Throughput} \ldots \text{ for } \mathrm{SF}>0 \text{ and } \mathrm{SF}<\mathrm{SF}_{Threshold}$$

$$SF \propto \frac{1}{\mathrm{Throughput}} \ldots \text{ for } SF > SF_{Threshold} \text{ and } SF < \infty$$

Scalar Factor (SF), Delay (D) and DTJ

$SF \propto D$ . . . for $SF>0$ and $SF<\infty$

$SF \propto DTJ$ . . . or $SF>0$ and $SF<\infty$

Scalar Factor (SF) and Node Life Time (L.)

$SF \propto L$ . . . for $SF>0$ and $SF<SF_{Threshold}$

Scalar Factor (SF) and Storage Occupation (SO)

$SF \propto SS$ . . . for $SF>0$ and $SF<SF_{Threshold}$

Scalar Factor (SF) and Congestion (Con)

$$SF \propto \frac{1}{\text{Con}} \ldots \text{ for } SF > 0 \text{ and } SF < \infty$$

Scalar Factor (SF) and Duplicated Arrival (Dup)

$$SF \propto \frac{1}{\text{Dup}} \ldots \text{ for } SF > 0 \text{ and } SF < \infty$$

TABLE 2

Performance Results Of Varying SF For Network C

	Base station Location Center Scalar Factor Value						
	0	0.1	0.5	1	2	5	10
Throughput	4703	15151	15147	15149	15115	14911	14795
Delay	0.00023	2.81936	14.0662	28.2405	60.2757	179.097	338.65
Delay Time Jitter	0.000117	3.82722	19.1394	38.3072	82.3954	275.467	529.082
Total energy dissipated/initial Energy	100%	100%	100%	100%	100%	100%	100%
number of Died Nodes	98	97	99	99	99	99	99
FND	1359.84	2086.26	2094.39	2109.57	2168.79	2824.1	4198.88
BND	1739.01	4066.32	4098.71	4208.72	4284.27	4938.21	7410.86
HND	2373.44	5837.21	5708.44	5743.14	5601.44	7090.23	10597.2
LND	0	0	10208.6	9992.52	9893.33	21002.3	14042.4
Congestion	68179	9448	9468	9771	21003	10768	7295
Duplicated Arrival	21007	21	24	22	34	88	80
Hop count/message	10	2	2	2	2	2	2
Frequency Memory Occupation	100907	235434	235809	236096	224432	164275	120261

TABLE 3

Performance Results Of Varying SF For Network O

	Base station Location Origin Scalar Factor Value						
	0	0.1	0.5	1	2	5	10
Throughput	2849	5677	5677	5691	5700	5709	5709
Delay	0.000271	2.86646	16.8269	30.4126	55.9837	89.3468	123.502
Delay Time Jitter	0.000263	6.10709	37.7896	73.5379	142.987	247.34	360.592
Total energy dissipated/ initial Energy	100%	100%	100%	100%	100%	100%	100%
number of Died Nodes	98	99	99	99	99	99	99
FND	500.902	539.444	580.26	641.373	753.441	1279.06	1939.52
BND	527.825	673.546	779.148	1039.54	1096.15	1657.5	2814.23
HND	572.273	1196.28	1234.54	1495.2	2212.02	3044.87	6546.16
LND	0	6680.52	6300.32	6187.31	6885.03	9217.4	12440.3
Congestion	333092	82959	84943	82712	79559	65579	33306
Duplicated Arrival	2958	29	28	17	8	4	2
Hop count/message	6	2	2	2	2	1	1
Occupied Memory	105137	152899	140212	135639	128915	115978	102606

TABLE 4

Performance Results Of Varying SF For Network A

	Base station Location Random location A Scalar Factor Value						
	0	0.1	0.5	1	2	5	10
Throughput	4608	16829	16828	16824	16740	16600	16551
Delay	0.00	2.53	12.60	25.34	53.87	160.13	313.35
Delay Time Jitter	0.00	3.87	19.30	39.07	82.48	257.99	514.29
Total energy dissipated/initial Energy	100%	100%	100%	100%	100%	100%	100%
number of Died Nodes	99	99	99	98	98	99	99
FND	968.92	2078.20	2094.26	2103.93	2070.06	2900.06	4264.82
BND	1468.19	3514.53	3565.95	3669.73	3654.33	4813.07	7980.79
HND	2231.52	5670.22	5642.78	5618.57	5568.54	7353.25	20471.40
LND	4045.43	21285.6	10722.4	0	0	12196	15107.7
Congestion	59851	6719	6699	7206	10333	9345	3974
Duplicated Arrival	12939	0	0	2	63	89	45
Hop count/message	13	2	2	2	2	2	2
Occupied Memory	102097	211501	212247	212165	195828	141750	107578

TABLE 5

Performance Results Of Varying SF For Network B

	Base station Location Random location B Scalar Factor Value						
	0	0.1	0.5	1	2	5	10
Throughput	4144	7567	7567	7568	7569	7564	7560
Delay	0.000192	1.84439	11.3982	19.1009	35.2904	54.8282	75.9604
Delay Time Jitter	0.000203	5.17728	32.673	61.2812	214.92	211.417	337.255
Total energy dissipated/ initial Energy	100%	100%	100%	100%	100%	100%	100%
number of Died Nodes	98	99	99	98	99	99	99
FND	510.505	531.274	575.872	630.981	749.733	1264	1938.52
BND	547.271	659.971	769.494	2048.08	1077.59	1621.04	2748.27
HND	595.085	1155.77	1213.54	1520.13	2208.63	3292.39	6758.26
LND	0	7768.55	7161.32	0	7750.04	10205	13478.8
Congestion	319063	82011	83002	84188	82214	67754	34298
Duplicated Arrival	3633	0	0	0	0	0	0
Hop count/message	5	1	1	1	1	1	1
Occupied Memory	101991	144951	131473	128186	120855	109025	97208

Varying D_{max}

Given simulation input of 40,000 simulation messages, 20 buffer size, mean inter-arrival time=0.5, initial energy per node=101e+7, duplicate factor=5, and scalar factor=0.5, results were achieved for D_{max}: 5, 10, 15, 20, and 25. Exemplary results are shown in FIGS. **20-32** and the following Table showing performance results of varying D_{max} for network O and network B according to one embodiment.

	Base station Location Origin (0, 0) Dmax Value				
	5	10	15	20	25
Throughput	979	5677	8723	8579	13045
Delay	16.9859	16.8269	8.13427	7.07226	4.75431
Delay Time Jitter	11.6656	37.7896	14.007	8.99029	5.79872
Total energy dissipated/initial Energy	9%	100%	100%	100%	100%
No. of Died Nodes	6	99	98	99	99
FND	7060.05	580.26	981.803	2019.74	1923.56
BND	7060.05	779.148	1378.63	2970.12	4173.6
HND	12185.7	1254.4	1882.66	3516.76	5107.06
LND	0	6300.32	0	4921.76	6795.97
Congestion	0	84943	250387	268554	274631
Duplicated Arrival	0	28	17	230	568
hop count/message	2	2	2	3	2
Occupied Memory (Sum)	6823	140212	296463	565839	784630

-continued

	Base station Location Random location B Dmax Value				
	5	10	15	20	25
Throughput	1743	7567	10625	15253	25016
Delay	17.5681	11.3982	6.13383	4.25857	2.56386
Delay Time Jitter	15.7286	32.673	12.2799	7.12527	5.69703
Total energy dissipated/initial Energy	9%	100%	100%	100%	100%
No. of Died Nodes	5	99	99	99	99
FND	9661.72	575.872	1199.78	2028.52	2873.03
BND	9661.72	769.494	1805.57	3627.81	6069.6
HND	15260.4	1233.72	2293.89	4464.72	7748.41
LND	0	7161.32	6074.36	7874.53	12532
Congestion	0	83002	210080	187736	103172
Duplicated Arrival	0	0	28	182	884
hop count/message	2	1	2	2	1
Occupied Memory (Sum)	5431	131473	327554	575144	878827

D_{max} vs. Throughput Delay and DTJ

D_{max} is inversely proportional to delay and DTJ as shown in FIGS. **21** and **22**. However, it is not always proportional to throughput; when a message spans the network, it generally causes a substantial amount of energy dissipation to receive the message by a large number of nodes. The immediately preceding table shows that exemplary throughput is reduced for D_{max}=25 in networks "A" and "C." It also shows a continuing increase in networks "O" and "B", since a distant base station became accessible for other parts of the network. Similarly, FIG. **22** shows an exemplary high DTJ value for D_{max}=10 compared to D_{max}=5. In this implementation, the selection of D_{max} is predetermined to network deployment, and it is restricted to the limitation of node resources and bandwidth.

D_{max} vs. Energy Dissipation, Number of Failed Nodes, FND, BND, HND, and LND

FIG. **22** shows that initial energy is consumed for different D_{max} values. In this exemplary implementation, the lowest dissipation is indicated for D_{max}=5, since approximately 49% of the nodes are inaccessible and isolated from other nodes and the base station. The relationship between D_{max}, FND, BND, HND, and LND depends on the layout of the network. FIGS. **26** and **27** respectively illustrate that approximately 20% and 50% of the nodes of networks "A" and "C" remain alive for D_{max}=10.

D_{max} vs. Storage Occupation, Duplicated Arrival, and Congestion

FIGS. **29**, **30**, and **31** show an exemplary increase in duplicated messages and associated high memory occupation compared to the average number of hops to reach the base station. Duplication occurs since more than one node will have similar timer value and will dissipate the message in the same time and before receiving base station ACK.

D_{max} vs. Hop Count

FIG. **32** shows escalating D_{max} minimizes hop count in networks "C" and "A". In networks "O" and "B", it increased since the base station can receive messages from the distant message in network through in multi-hop fashion.

Discussion on D_{max}

The previous section shows that the effect of D_{max} is different from one network to another. Essentially, D_{max} value is hardware dependent. Large D_{max} dissipates large energy for receiving. In most cases, a very large D_{max} is not supported and routing is multi-hop. For this, its value should be determined according to the location of the base station, deployment area, and deployment schema. The following proportions between D_{max} and other measures were used:

D_{max} and Throughput (Thro.):

$\mathrm{Dmax} \propto \mathrm{Throughput} \ldots \text{ for } D_{max}>0 \text{ and } SF<D_{maxThreshold}$

$$\mathrm{Dmax} \propto \frac{1}{\mathrm{Throughput}} \ldots \text{ for } D_{maxThreshold} > 0 \text{ and } D_{max} < \infty$$

D_{max} and Delay:

$$\mathrm{Dmax} \propto \frac{1}{D} \ldots \text{ for } D_{max} > 0 \text{ and } D_{max} < \infty$$

D_{max} and Congestion (Con):

$\mathrm{Dmax} \propto \mathrm{Con} \ldots \text{ for } D_{max}>0 \text{ and } D_{max}<\infty$

D_{max} and Duplicated arrival (Dup):

$\mathrm{Dmax} \propto \mathrm{Dup} \ldots \text{ for } D_{max}>0 \text{ and } D_{max}<\infty$

Varying Buffer Size

Buffer size is proportional to throughput and inversely proportional to delay, conjunction, and duplicated arrival. Maximizing buffer size allows more messages to be stored and routed later. Given simulation input of 40,000 simulation messages, D_{max}=10, mean inter-arrival time=0.5, initial energy per node=101e+7, duplicate factor=5, and D_{max}=10 m, extracted results for buffer size values: 5, 10, 15, and 20. Exemplary results are shown in FIGS. **33-43** and the following two tables. The following two tables respectively show performance results of varying the buffer size for networks A and C, and performance results of varying the buffer size for networks B and O according to one embodiment.

	Base station Location							
	Location A				Centric			
	Buffer Size Value							
	5	10	15	20	5	10	15	20
Throughput	16693	16819	16829	16828	15041	15142	15147	15147
Delay	13.27	12.81	12.63	12.60	15.8171	14.4234	14.0763	14.0662
Delay Time Jitter	20.45	19.63	19.35	19.30	21.5974	19.5582	19.1264	19.1394
Total energy dissipated/ initial Energy	100%	100%	100%	100%	100%	100%	100%	100%
No. of Died Nodes	99	98	99	99	99	98	99	99
FND	1728.57	2092.36	2094.26	2094.26	2057.12	2094.26	2094.39	2094.39
BND	3753.46	3774.94	3565.95	3565.95	3974.86	4068.84	4098.71	4098.71
HND	5595.06	5665.93	5682.95	5642.78	5450	5735.04	5708.29	5708.44
LND	11233.1	0	10816.3	10722.4	10281.9	0	10240.3	10208.6
Congestion	11763	7397	6772	6699	13791	9848	9493	9468
Duplicated Arrival	66	3	0	0	70	30	24	24
hop count/message	2	2	2	2	2	2	2	2
Occupied Memory (Sum)	185062	210859	211829	212247	210067	234281	235529	235809

	Base station Location							
	Origin (0, 0)				Location B			
	Buffer Size Value							
	5	10	15	20	5	10	15	20
Throughput	5697	5686	5680	5677	7565	7567	7567	7567
Delay	12.3398	14.0311	15.1507	16.8269	7.73483	8.92752	10.6559	11.3982
Delay Time Jitter	31.2802	33.261	35.8335	37.7896	26.0107	28.5202	32.649	32.673
Total energy dissipated/initial Energy	100%	100%	100%	100%	100%	100%	100%	100%
No. of Died Nodes	99	98	99	99	99	99	99	99
FND	630.084	594.85	592.087	580.26	613.779	592.772	584.542	575.872
BND	1050.47	1035.36	859.158	779.148	1017.39	981.397	918.847	769.494
HND	2842.43	1699.67	1351.9	1234.54	3170.77	1577.83	1317.38	1213.54
LND	8895.99	0	7510.84	6300.32	10476.3	9460.8	8010.39	7161.32
Congestion	63422	62985	78731	84943	60590	69276	78755	83002
Duplicated Arrival	11	21	25	28	0	0	0	0
hop count/message	2	2	2	2	1	1	1	1
Occupied Memory (Sum)	123306	126690	136371	140212	113019	121933	127128	131473

Buffer Size vs. Throughput Delay, DTJ

FIGS. **33**, **34**, and **35**, respectively, show how increasing buffer size typically improves throughput for all networks. FIGS. **33** and **34** show how delay and DTJ increased in networks "B" and "O", because more messages were able to reach the base station responsive to an increase in the amount of message storage capacity of intermediate/transient nodes. The same figures show a very small change in throughput for increasing buffer size from 10 to 20, which implies the CEER's efficiency is not restricted to particular amounts of data storage allocations. For all monitored networks, it is sufficient to include a realistic storage area without extra storage.

Buffer Size vs. Energy Dissipation Number of Failed Nodes, FND, BND, HND, and LND

The effect of buffer size over various measures is shown in FIGS. **35** to **43**. These Figs. show, for example, that there is a minimal relationship between buffer size and energy dissipation. The number of blocked messages for memory shortage arises and re-transmission operations are minimized; for this reason; its effect over energy dissipation is unpredictable.

Buffer Size vs. Storage Sharing, Duplicated Arrival, Hop Counts, and Congestion

FIGS. **44**, **45**, and **46** show that congestion, duplicated arrival, and memory sharing is optimized with increasing buffer size.

Discussion on Buffer Size Variation

Previous sections show the improvement in performance measures while buffer size increases. However, this improvement is not proportional to buffer size. It is sufficient to include a realistic storage size and also to take the advantage of duplication factor to manage the available storage.

Buffer Size (But) and Throughput (Thro.):

$\mathrm{Buf} \propto \mathrm{Throughput} \ldots \text{for } \mathrm{Buf} > 0 \text{ and } \mathrm{Buf} < \mathrm{Buf}_{Threshold}$

Buffer Size (But) and Congestion (Con):

$$\mathrm{Buf} \propto \frac{1}{\mathrm{Con}} \ldots \text{ for Buf} > 0 \text{ and Buf} < Buf_{Threshold}$$

Buffer Size (But) and Duplicated arrival (Dup):

$$SF \propto \frac{1}{\mathrm{Buf}} \ldots \text{ for Buf} > 0 \text{ and Buf} < Buf_{Threshold}$$

Buffer Size (But) and Storage occupation (SS)

$SF \propto SS \ldots \text{for } \mathrm{Buf} > 0 \text{ and } \mathrm{Buf} < \mathrm{Buf}_{Threshold}$

Varying Duplication Factor

Proper utilization of the duplication factor saves memory by limiting long message storage under the premise that such messages are stored by neighboring nodes. The particular value given to the duplication factor is arbitrary, but in any event, it is carefully considered to avoid message loss and to provide appropriate memory management. Given exemplary simulation input of 40,000 simulation messages, buffer size=20, mean inter-arrival time=0.5, initial energy per node=101e+7, and D_{max}=10 m, exemplary results utilizing duplication factor values: 1, 2, 4, and 8, are shown in FIGS. **47-59** and the following two tables. The following two tables respectively show performance results of varying the duplication factor for networks A and C, and (the second table) performance results of varying the duplication factor for networks B and O according to one embodiment.

Duplication Factor vs. Storage Occupation, Duplicated Arrival, Hop Counts, and Congestion

FIGS. **56**, **57**, **58**, and **59** show that congestion, duplicated arrival, and memory sharing is affected by increasing duplication factor. A higher value for this factor generally increases duplicated arrival and congestion. On the other hand, such duplication factor value typically increases memory sharing.

Discussion on the Mean Inter-Arrival (MIT)

MIT has a relatively minor role related to the duplication factor in saving both memory and energy. The optimal value for duplication depends on available storage, number of nodes, and deployment. For example:

	Base station Location							
	Random A				Centric			
	Duplication Factor Value							
	1	2	4	8	1	2	4	8
Throughput	7679	15474	16823	16825	6829	14853	15166	15157
Delay	0.00	14.89	12.99	11.67	8.63684E−05	15.7574	14.7055	13.1348
Delay Time Jitter	0.00	22.03	19.45	18.09	0.000010457	22.3649	19.4083	17.9672
Total energy dissipated/ initial Energy	46%	90%	100%	100%	46%	92%	100%	100%
No. of Died Nodes	0	51	99	99	0	56	98	99
FND	0.00	3403.07	2143.93	2086.60	0	4053.48	2603.33	2094.26
BND	0.00	8071.60	3900.62	3489.31	0	7626.29	4486.14	3842.34
HND	0.00	19128.90	6027.44	5230.37	0	15683.6	6168.45	5170.93
LND	0	0	11584.8	10219.4	0	0	0	9445.87
Congestion	0	7686	11849	1236	0	7569	13714	1679
Duplicated Arrival	0	0	4	5	0	0	22	17
hop count/message	1	2	2	2	1	2	2	2
Occupied Memory (Sum)	4524	131865	216977	205257	2174	159085	243450	223808

	Base station Location							
	Origin				Random B			
	Duplication Factor Value							
	1	2	4	8	1	2	4	8
Throughput	2379	4614	5676	5683	3198	4244	7568	7567
Delay	0.00009	9.9849	15.8658	16.1377	8.25E−05	7.68793	9.8359	10.6018
Delay Time Jitter	1.31798E−11	20.3929	36.9605	37.6834	1.39E−05	19.1283	29.9006	32.3445
Total energy dissipated/initial Energy	44%	67%	100%	100%	44%	62%	100%	100%
No. of Died Nodes	0	16	99	99	0	14	99	99
FND	0	1778.42	593.887	579.042	0	1900.16	584.282	568.292
BND	0	0	916.599	690.98	0	0	907.325	695.672
HND	0	0	1954.72	907.112	0	0	1907.44	860.213
LND	0	0	10052.3	4433.22	0	0	11343.3	5541.42
Congestion	0	8813	74922	66544	0	6728	74186	66574
Duplicated Arrival	0	0	31	23	0	0	0	0
hop count/message	1	2	2	2	1	1	1	1
Occupied Memory (Sum)	2047	49562	139594	121189	5453	32022	129203	112627

Duplication Factor Vs. Throughput Delay, and DTJ

FIGS. **47**, **48**, and **49** show that, in certain exemplary circumstances, increasing the duplication factor value from 1 to 4 improves throughput for substantially all networks. A small value for duplication factor typically results in message loss.

Duplication Factor vs. Energy Dissipation Number of Failed Nodes, FND, BND, HND and LND

The effect of duplication factor over these measures is shown in FIGS. **50** to **55**. The impact of duplication factor over these measures is similar to the buffer size.

Duplication factor (DF) and Throughput (Thro.):

$DF \propto$ Throughout . . . for DF>0 and DF<$DF_{Threshold}$

Duplication factor (DF) and Storage occupation (SO):

$DF \propto SS$ . . . for DF>0 and DF<$DF_{Threshold}$

Varying Mean Inter-Arrival Time

The inter-arrival time is an environment-dependent variable. In an exemplary simulation input of 40,000 simulation messages, buffer size=20, initial energy per node=101e+7, duplicate factor=5, and D_{max}=10 m, exemplary results for mean inter-arrival values include: 0.1, 0.5, 1, and 2, as illustrated in FIGS. **60-62** and the following two tables. The following two tables respectively show (first table) performance results of varying mean inter-arrival time for networks A and C, and (second table) performance results of varying mean inter-arrival time for networks B and O according to one embodiment.

Mean Inter-Arrival Time vs. Storage Occupation, Duplicated Arrival, Hop Counts, And Congestion

FIGS. **69**, **70**, **71**, and **72** show that congestion, duplicated arrival, and memory sharing is affected by increasing mean inter-arrival time. A higher value for MIT allows more messages to be stored in key nodes (within base station distance) and for this utilizing memory is decreased, where duplicated arrival and congestion increase.

	Base station Location							
	Random A				Centric			
	Mean inter-arrival time							
	0.1	0.5	1	2	0.1	0.5	1	2
Throughput	16699	16828	16749	16749	15059	15147	15100	15096
Delay	15.62	12.60	12.17	12.01	16.4276	14.0662	14.6814	14.4741
Delay Time Jitter	23.33	19.30	20.09	19.90	21.8489	19.1394	20.6659	20.6058
Total energy dissipated/initial Energy	100%	100%	100%	100%	100%	100%	100%	100%
No. of Died Nodes	98	99	99	99	98	99	98	98
FND	421.45	2094.26	5590.70	11172.50	476.586	2094.39	5660.58	11293.9
BND	861.32	3565.95	8190.21	16331.50	939.155	4098.71	8826.3	17627.7
HND	1328.05	5642.78	13818.20	26749.30	1310.64	5708.44	13801.7	27261.4
LND	0	10722.4	28595.9	57699.6	0	10208.6	0	0
Congestion	24910	6699	17418	17428	25738	9468	19162	18972
Duplicated Arrival	60	0	75	74	52	24	105	105
hop count/message	2	2	2	2	2	2	2	2
Occupied Memory (Sum)	192689	212247	222853	222208	223155	235809	253356	252455

	Base station Location							
	Origin				Random B			
	Mean inter-arrival time							
	0.1	0.5	1	2	0.1	0.5	1	2
Throughput	5704	5677	5020	4894	7568	7567	5157	4937
Delay	11.3586	16.8269	9.38026	9.58845	6.823	11.3982	6.94545	6.75798
Delay Time Jitter	28.4089	37.7896	20.2107	20.1062	23.9872	32.673	19.524	18.3907
Total energy dissipated/initial Energy	100%	100%	87%	81%	100%	100%	84%	80%
No. of Died Nodes	99	99	41	35	99	99	37	31
FND	215.049	580.26	1342.24	2522.64	213.898	575.872	1321.78	2592.99
BND	341.67	779.148	5259.94	19926	345.367	769.494	4205.4	22036.4
HND	853.407	1234.54	0	0	826.817	1213.54	0	0
LND	2406.44	6300.32	0	0	2529.46	7161.32	0	0
Congestion	77036	84943	24640	19272	87178	83002	26844	17419
Duplicated Arrival	6	28	0	3	0	0	0	0
hop count/message	2	2	1	2	1	1	1	1
Occupied Memory (Sum)	134246	140212	81581	72215	127462	131473	70678	59077

Mean Inter-Arrival Time Vs. Throughput Delay, and DTJ

FIGS. **60**, **61**, and **62** show that increasing mean inter-arrival time (MIT) value from 0.1 to 2 typically improves throughput for all networks, especially for networks "B" and "O." However, this effect is relatively small, as compared to exemplary impact on data throughput as a result of utilizing other factors.

Mean Inter-Arrival Time vs. Energy Dissipation, Number Of Failed Nodes, FND, BND, HND, And LND

The effect of these measures is shown in FIGS. **63** to **68**. Increasing MIT increases the values of these measures.

Discussion on the Variation of Mean Inter-Arrival

Previous sections show that MIT has a small role on performance measures compared to other factors. Its value is not to be manipulated as it is controlled by the sensed environment. A proportional relationship with MIT was determined.

Mean inter-arrival time (MIT) and network lifetime (LT.):

$MIT \propto LT$ . . . for MIT>0 and MIT<∞

Varying Number of Nodes

Network size is determined by number of nodes deployment area. CEER was examined with different number of nodes within network. Results were extracted for a network size of 30, 50, 75 and 100 nodes. Results are shown in FIGS. **73***a-d* and **74**, and the following two tables. The following two tables respectively show (first table) performance results of varying number of nodes for network A and C, and (table 2) performance results of varying number of nodes for network B and O, according to one embodiment.

	Base station Location							
	Random A				Centric			
	No. of nodes							
	30	50	75	100	30	50	75	100
Throughput	8603	14278	22901	30010	8240	11864	20549	26806
Delay	2.62	3.55	3.68	4.31	3.07972	4.92181	4.92967	4.73355
Delay Time Jitter	4.23	6.70	7.92	8.97	4.05343	6.96269	8.01306	7.90716
Total energy dissipated/initial Energy	93%	100%	100%	100%	93%	100%	100%	100%
No. of Died Nodes	26	48	74	99	27	49	74	99
FND	1693.53	1911.10	3044.03	4014.72	1990.23	2245.77	3399.11	4845.97
BND	1996.52	2762.72	4794.98	7109.00	3269.51	3824.13	6174.44	8391.61
HND	3293.81	4654.72	7237.51	10375.70	4123.97	5077.81	8379.96	11328.8
LND	0	0	12369.2	15830.9	0	6574.04	10640.8	13872.7
Congestion	0	83	756	1970	0	159	664	1068
Duplicated Arrival	135	19	174	577	518	605	829	1217
hop count/message	1	1	1	1	2	2	2	2
Occupied Memory (Sum)	33708	105934	236620	432700	38807	121814	269696	492488

	Base station Location							
	Origin				Random B			
	No. of nodes							
	30	50	75	100	30	50	75	100
Throughput	1988	3956	7778	8723	3970	4928	8740	10625
Delay	0.00009	9.01362	5.50506	8.13427	5.81345	8.09174	6.42461	6.13383
Delay Time Jitter	1.58E−11	13.3798	10.5681	14.007	8.37078	13.0956	13.1421	12.2799
Total energy dissipated/ initial Energy	7%	100%	100%	100%	100%	100%	100%	100%
No. of Died Nodes	1	49	74	98	29	49	74	99
FND	14297.9	562.133	851.269	981.803	659.018	620.91	972.499	1199.78
BND	0	762.143	1143.97	1378.63	902.334	896.211	1325.52	1805.57
HND	0	970.418	1534.4	1882.66	1100.28	1170.37	1705.16	2293.89
LND	0	2945	4969.98	0	2708.32	3345.89	4969.21	6074.36
Congestion	0	37280	111420	250387	3037	36446	104448	210080
Duplicated Arrival	0	0	14	17	0	13	30	28
hop count/message	1	2	1	2	2	2	2	2
Occupied Memory (Sum)	0	73155	172880	296463	36503	77528	181838	327554

Number of Nodes vs. Throughput Delay, and DTJ

FIGS. **73***a-d*, **74**, and **75**, show that increasing the number of nodes in a network improves throughput for all networks as expected. However, it doesn't have significant affect on delay and DTJ.

Number of Nodes vs. Energy Dissipation, Number of Failed Nodes, FND, BND, HND, and LND

The effect over these measures is shown in FIGS. **76** to **80**. Increasing the number of nodes in a network maximizes network lifetime and also increases the values of all these measures.

Number of Nodes vs. Storage Occupation Duplicated Arrival Hop Count, and Congestion

FIGS. **81**, **82**, **83**, and **84** show that congestion, duplicated arrival, and memory sharing is affected by increasing the number of nodes in a network. Introducing more number of nodes allows more messages to be stored and, thus, more memory occupation. Also, the probability of conjunction and duplicated arrival are also increased.

Discussion on the Variation of Number of Nodes

One of the most important features required in any routing protocol is flexibility to accommodate changes in network size (scalability) and traffic load. This last section shows that CEER is not affected negatively to the variation in network size. The following proportional with number of nodes in network was obtained:

number of nodes (NN) and Throughput (Thr.):
$NN \propto Thr$ . . . for $NN>0$ and $NN<\infty$
number of nodes (NN) and network lifetime (LT.):
$NN \propto LT$ . . . for $NN>0$ and $NN<\infty$
number of nodes (NN) and storage occupation (SO):
$NN \propto SO$ . . . for $NN>0$ and $NN<\infty$

CONCLUSION

Although the above sections describe cooperative packet routing for wireless sensor networks in language specific to structural features and/or methodological operations or actions, the implementations defined in the appended claims are not necessarily limited to the specific features or actions described. Rather, the specific features and operations for cooperative packet routing for wireless sensor networks are disclosed as exemplary forms of implementing the claimed subject matter.

The invention claimed is:

1. In a wireless sensor network comprising multiple sensor nodes and a base station, a method implemented by a sensor node of the sensor nodes for cooperative packet routing, the method comprising:

receiving a packet transmitted by a source node of the sensor nodes, the packet being targeted for receipt by the base station;

responsive to receiving the packet, determining an amount of energy remaining in the sensor node; and

if the amount of energy meets a configurable energy threshold designed to increase lifetime of the sensor node, implementing cooperative packet routing operations for conditional re-transmission of the packet to the base station, the conditional re-transmission being based on the sensor node delaying packet re-transmission by a variable address-based timer;

the conditional re-transmission being based on delaying packet re-transmission by a variable address-based timer;

wherein the variable address-based timer is determined based on a node address difference between the address of the node that generates the packet and the address of the sensor node that receives the packet and a scaling factor.

2. The method of claim **1**, wherein the configurable energy threshold is based on estimated respective amounts of energy used by the sensor node to sense data, perform computations, and engage in wireless communications.

3. The method of claim **1**, wherein the packet re-transmission criteria is based on one or more of the base station location, packet origin, and packet arrival time.

4. The method of claim **1**, wherein determining the amount of energy remaining in the sensor node comprises:

calculating an amount of energy dissipated responsive to receiving the packet from the source node; and

responsive to the calculating, updating a persisted energy value for the sensor node to account for the amount of energy dissipated responsive to receiving the packet.

5. The method of claim **1**, wherein the cooperative packet routing operations comprise:

decrementing a timer value of the variable address-based timer at periodic intervals; and

if an acknowledgement that the base station has received the packet has not been received before expiration of the timer value:

inserting an address assigned to the sensor node to the packet, the address for use by one or more other sensor nodes of the sensor nodes responsive to receipt of the packet to calculate respective timer values controlling respective re-transmission of the packet by the one or more other sensor nodes; and

transmitting the packet for receipt by the base station.

6. The method of claim **1**, wherein the cooperative packet routing operations further comprise:

if the packet has already been received a duplicate factor number of times, reducing a number of sensor nodes in the wireless sensor network participating in cooperative data transfer of the packet to the base station, the reducing comprising:

not re-transmitting the packet;

canceling any prior scheduled re-transmission event associated with a duplicate of the packet received earlier by the sensor node; and

freeing any memory resources associated with the packet and any duplicates of the packet; and

wherein the reducing is based on a sensor node operational redundancy in the wireless sensor network to conserve sensor node operational life and transmit the packet to the base station, the sensor node operational redundancy being a likelihood that a different node of the sensor nodes will transmit the packet to the base station.

7. The method of claim **6**, wherein the cooperative packet routing operations further comprise:

estimating an amount of energy dissipated by the sensor node responsive to performing operations; and

updating a persisted energy value for the sensor node to account for the amount of energy.

8. The method of claim **1**, further comprising if the amount of energy does not meet the configurable energy threshold:

discarding the packet;

freeing any memory resources associated with maintaining the packet;

maintaining operational capabilities for the sensor node to sense and transmit data to the base station; and

wherein the packet is not re-transmitted by the sensor node.

9. A sensor node for use in a wireless sensor network, the wireless sensor network including multiple sensor nodes and a base station, the sensor node comprising:

a processor; and

a memory coupled to the processor, the memory comprising computer program instructions executable by the processor, the computer program instructions when executed by the processor for performing operations comprising:

receiving a packet transmitted by a source node of the sensor nodes the packet being targeted for receipt by the base station;

responsive to receiving the packet, determining an amount of energy remaining in the sensor node; and

if the amount of energy meets a configurable energy threshold designed to increase lifetime of the sensor node, implementing, by the sensor node, cooperative packet routing operations for conditional re-transmission of the packet to the base station, the conditional re-transmission being based on delaying packet re-transmission by a variable address-based timer;

wherein the variable address-based timer is determined based on a node address difference between the address of the node that generates the packet and the address of the sensor node that receives the packet and a scaling factor.

10. The sensor node of claim **9**, wherein the configurable energy threshold is based on estimated respective amounts of energy used by the sensor node to sense data, perform computations, and engage in wireless communications.

11. The sensor node of claim **9**, wherein the packet re-transmission criteria is based on one or more of the base station location, packet origin, and packet arrival time.

12. The sensor node of claim **9**, wherein the computer program instructions for determining the amount of energy remaining in the sensor node further comprise instructions for:

calculating an amount of energy dissipated responsive to receiving the packet from the source node; and

responsive to the calculating, updating a persisted energy value for the sensor node to account for the amount of energy dissipated responsive to receiving the packet.

13. The sensor node of claim **9**, wherein the computer program instructions for the cooperative packet routing operations further comprise instructions for:

decrementing a timer value of the variable address-based timer at periodic intervals; and

if an acknowledgement that the base station has received the packet has not been received before expiration of the timer value:

inserting an address assigned to the sensor node to the packet, the address for use by one or more other sensor nodes of the sensor nodes responsive to receipt of the packet to calculate respective timer values controlling respective re-transmission of the packet by the one or more other sensor nodes; and

transmitting the packet for receipt by the base station.

14. The sensor node of claim **9**, wherein the computer program instructions for the cooperative packet routing operations further comprise instructions for:

if the packet has already been received a duplicate factor number of times:

not re-transmitting the packet;

canceling any prior scheduled re-transmission event associated with a duplicate of the packet received earlier by the sensor node; and

freeing any memory resources associated with the packet and any duplicates of the packet.

15. The sensor node of claim **14**, wherein the computer program instructions for the cooperative packet routing operations further comprise instructions for:

estimating an amount of energy dissipated by the sensor node responsive to performing operations of claim; and

updating a persisted energy value for the sensor node to account for the amount of energy.

16. The sensor node of claim **9**, wherein the computer program instructions further comprise, if the amount of energy does not meet the configurable energy threshold, instructions for:

discarding the packet;

freeing any memory resources associated with maintaining the packet;

maintaining operational capabilities for the sensor node to sense and transmit data to the base station; and

wherein the packet is not re-transmitted by the sensor node.

17. A tangible non-transitory computer-readable data storage medium for using in a sensor node, the sensor node for deployment in a wireless sensor network of multiple sensor nodes and a base station, the tangible computer-readable data storage medium comprising computer program instructions executable by a processor, the computer program instructions when executed by the processor for performing operations comprising:

receiving a packet transmitted by a source node of the sensor nodes, the packet being targeted for receipt by the base station;

responsive to receiving the packet, determining an amount of energy remaining in the sensor node;

if the amount of energy meets a configurable energy threshold designed to increase lifetime of the sensor node, implementing cooperative packet routing operations for conditional re-transmission of the packet to the base station, the conditional re-transmission being based on randomizing packet re-transmission criteria; and

wherein operations for implementing cooperative packet routing operations comprise: calculating a timer value using an address of the sensor node and a scalar factor; decrementing the timer value at periodic intervals; and

if an acknowledgement that the base station has received the packet has not been received before expiration of the timer value:

inserting an address assigned to the sensor node to the packet, the address for use by one or more other sensor nodes of the sensor nodes responsive to receipt of the packet to calculate respective timer values controlling respective re-transmission of the packet by the one or more other sensor nodes; and

transmitting the packet for receipt by the base station.

18. The tangible non-transitory computer-readable data storage medium of claim **17** wherein the computer program instructions for the cooperative packet routing operations further comprise instructions for:

if the packet has already been received a duplicate factor number of times, reducing a number of sensor nodes in the wireless sensor network participating in cooperative data transfer of the packet to the base station, the reducing comprising:

not re-transmitting the packet;

canceling any prior scheduled re-transmission event associated with a duplicate of the packet received earlier by the sensor node; and

freeing any memory resources associated with the packet and any duplicates of the packet; and

wherein the reducing is based on a likelihood of sensor node operational redundancy in the wireless sensor network to conserve sensor node operational life and transmit the packet to the base station, the sensor node operational redundancy being a likelihood that a different node of the sensor nodes will transmit the packet to the base station.

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