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Urgaonkar et al.

(54) **CHANNEL ASSIGNMENT PROCESSES FOR HIGH DENSITY MULTI-CHANNEL MULTI-RADIO (MC-MR) WIRELESS NETWORKS**

(71) Applicants: **Rahul Urgaonkar**, Waltham, MA (US); **Subramanian Ramanathan**, Westford, MA (US); **Jason Redi**, Belmont, MA (US); **William Nii Tetteh**, Cambridge, MA (US)

(72) Inventors: **Rahul Urgaonkar**, Waltham, MA (US); **Subramanian Ramanathan**, Westford, MA (US); **Jason Redi**, Belmont, MA (US); **William Nii Tetteh**, Cambridge, MA (US)

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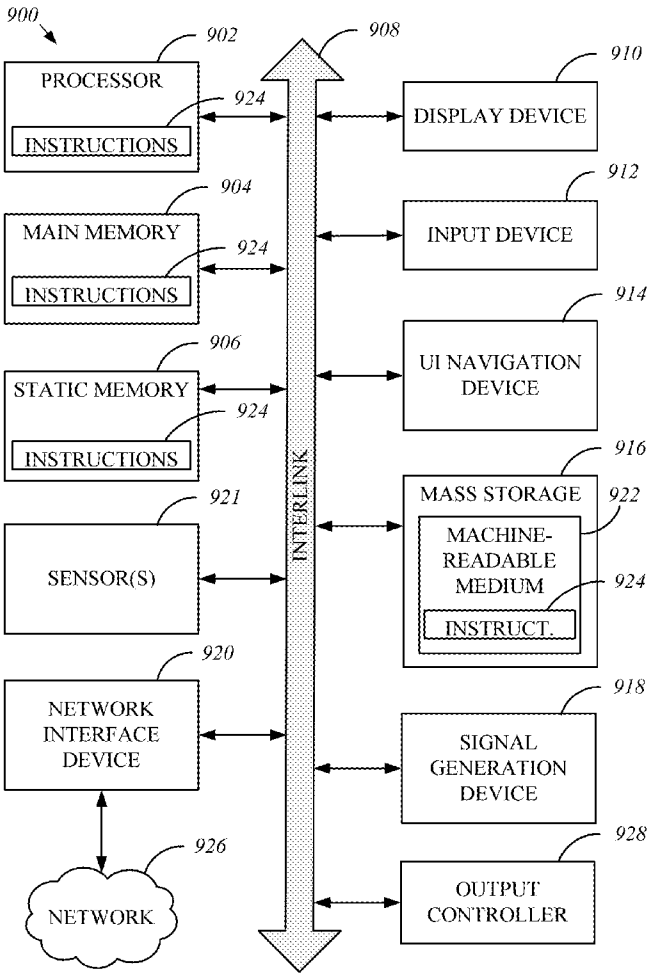
USPC **370/254**

(57) **ABSTRACT**

Embodiments for providing channel assignments for high density multi-channel multi-radio (MC-MR) wireless networks are generally described herein. In some embodiments, N nodes are provided in the network. T transceiver node groups are provided that include a first number of groups of nodes, wherein the first number of groups of nodes for a first of the T transceiver node groups have the N nodes assigned consecutively with a second number of nodes per each of the groups of nodes being a function of N. The first number of group of nodes for a remaining number of the transceiver node groups comprises N nodes with transceivers arranged to provide access to any node within a predetermined number of hops. The arrangement of the second number of nodes per each of the groups of nodes in the T transceiver node groups provides an optimized throughput per node.



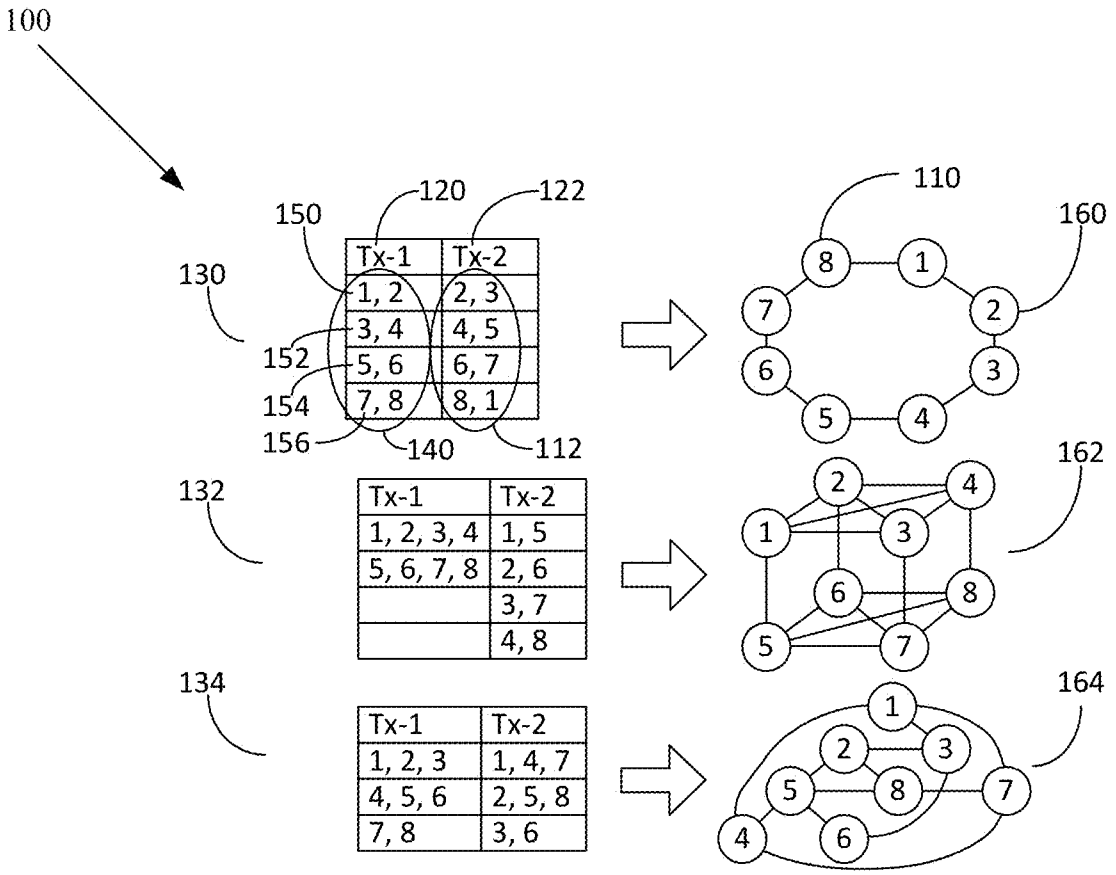

100
150
120
122
130
Tx-1
Tx-2
1, 2
2, 3
3, 4
4, 5
5, 6
6, 7
7, 8
8, 1
152
154
156
140
112
110
160
132
Tx-1
Tx-2
1, 2, 3, 4
1, 5
5, 6, 7, 8
2, 6
3, 7
4, 8
162
134
Tx-1
Tx-2
1, 2, 3
1, 4, 7
4, 5, 6
2, 5, 8
7, 8
3, 6
164

Fig. 1

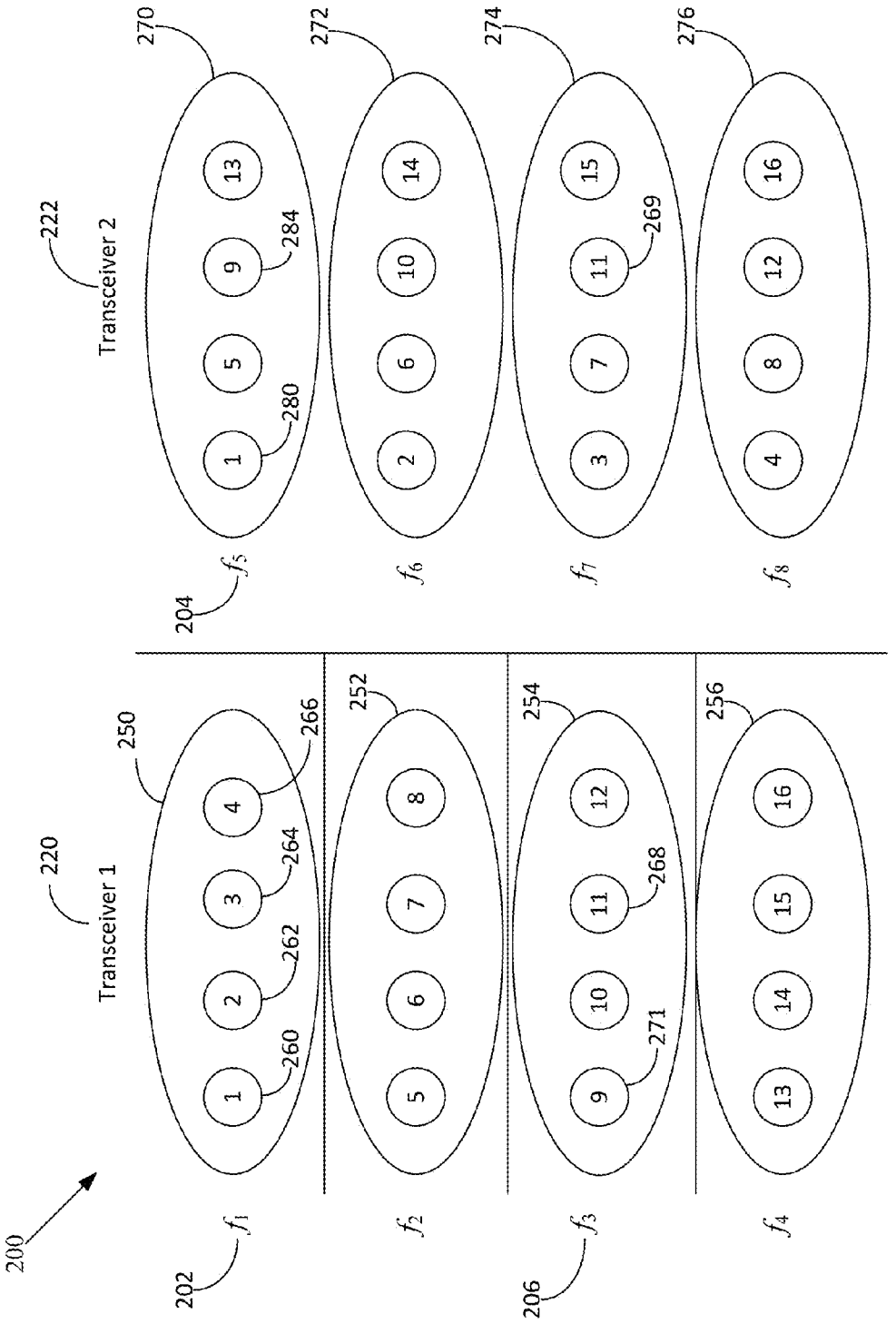

200
220
Transceiver 1
222
Transceiver 2
250
252
254
256
270
272
274
276
202
204
206
f_1
f_2
f_3
f_4
f_5
f_6
f_7
f_8
260
262
264
266
268
269
271
280
284

Fig. 2

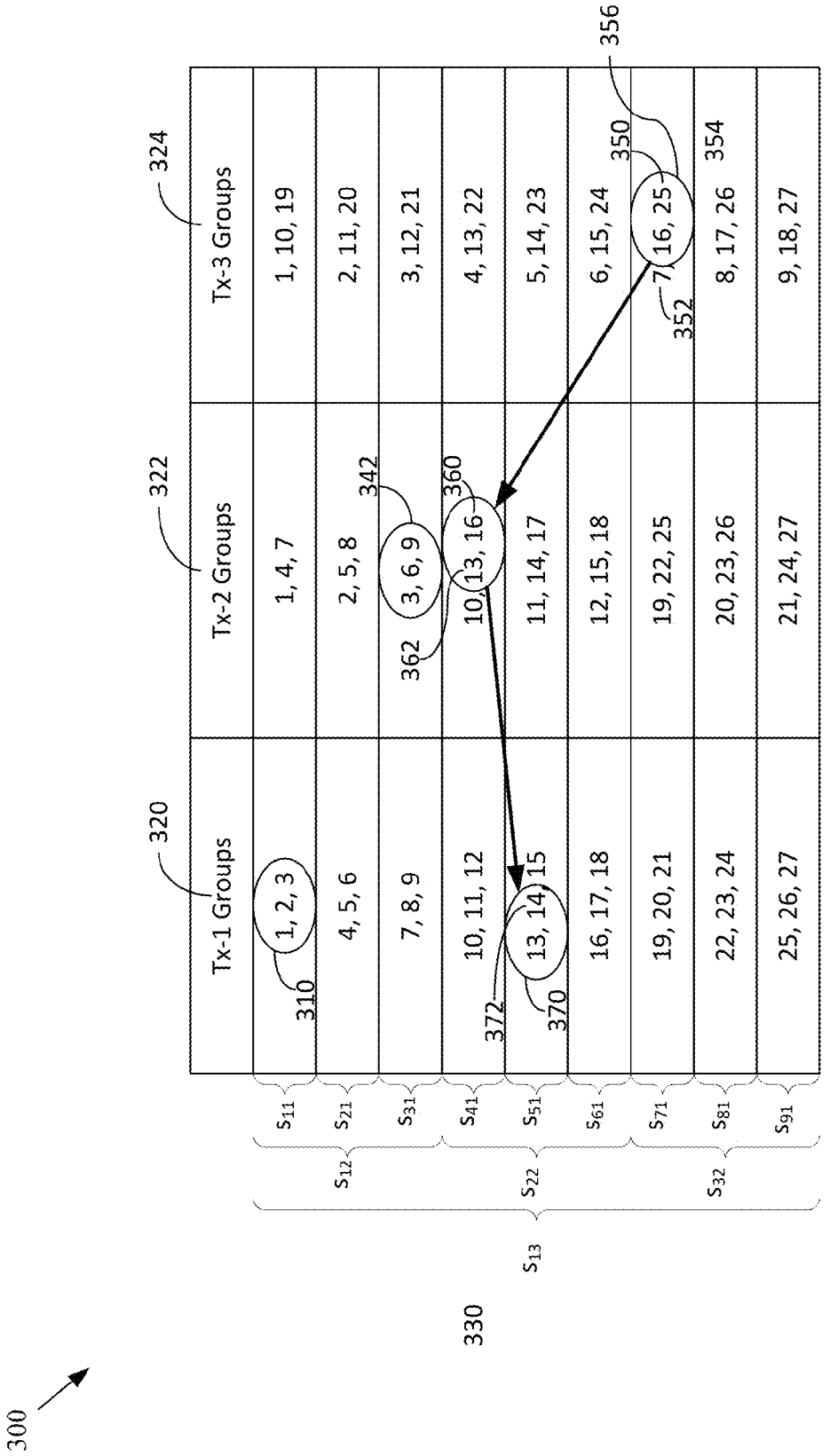

300
330
320
Tx-1 Groups
322
Tx-2 Groups
324
Tx-3 Groups
1, 2, 3
4, 5, 6
7, 8, 9
10, 11, 12
13, 14, 15
16, 17, 18
19, 20, 21
22, 23, 24
25, 26, 27
1, 4, 7
2, 5, 8
3, 6, 9
10, 13, 16
11, 14, 17
12, 15, 18
19, 22, 25
20, 23, 26
21, 24, 27
1, 10, 19
2, 11, 20
3, 12, 21
4, 13, 22
5, 14, 23
6, 15, 24
16, 25, 7
8, 17, 26
9, 18, 27
310
342
360
362
372
370
356
350
352
354
S11
S21
S31
S41
S51
S61
S71
S81
S91
S12
S22
S32
S13

Fig. 3

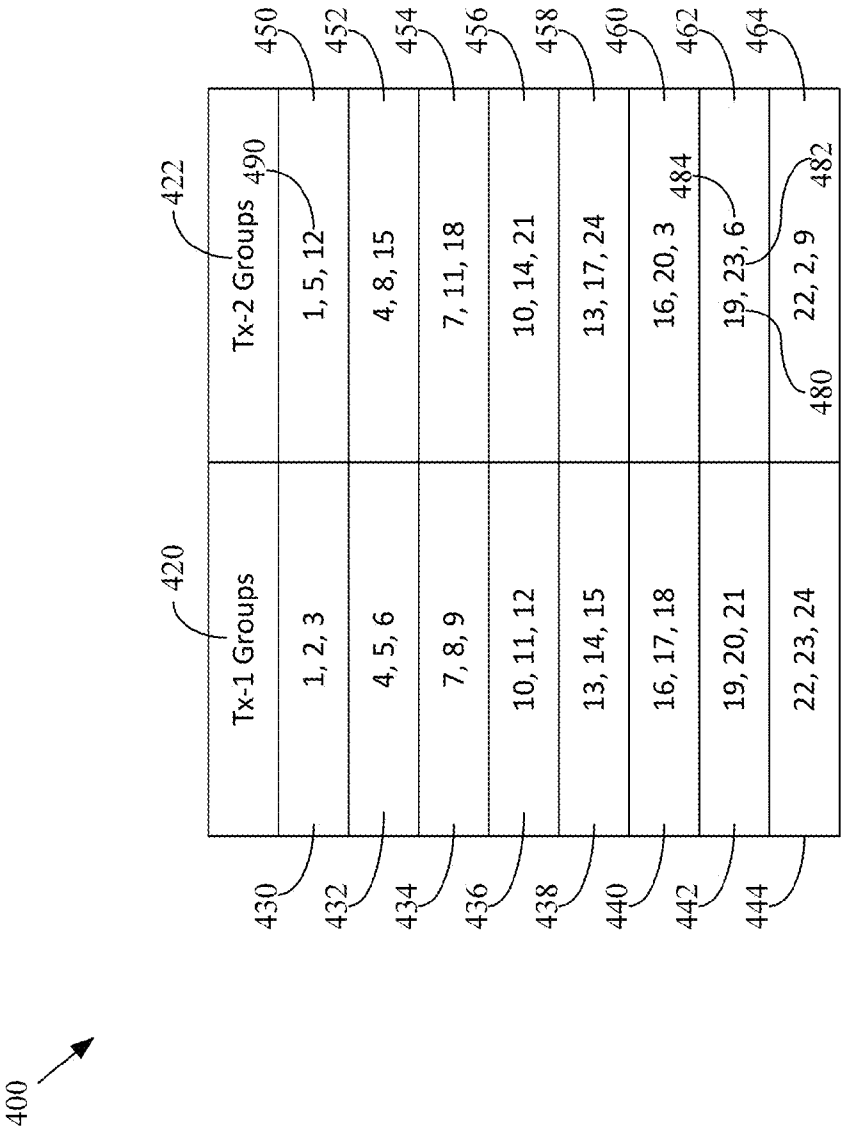

400
420
Tx-1 Groups
422
Tx-2 Groups
490
1, 2, 3
1, 5, 12
4, 5, 6
4, 8, 15
7, 8, 9
7, 11, 18
10, 11, 12
10, 14, 21
13, 14, 15
13, 17, 24
16, 17, 18
16, 20, 3
19, 20, 21
19, 23, 6
22, 23, 24
22, 2, 9
480
482
484
430
432
434
436
438
440
442
444
450
452
454
456
458
460
462
464

Fig. 4

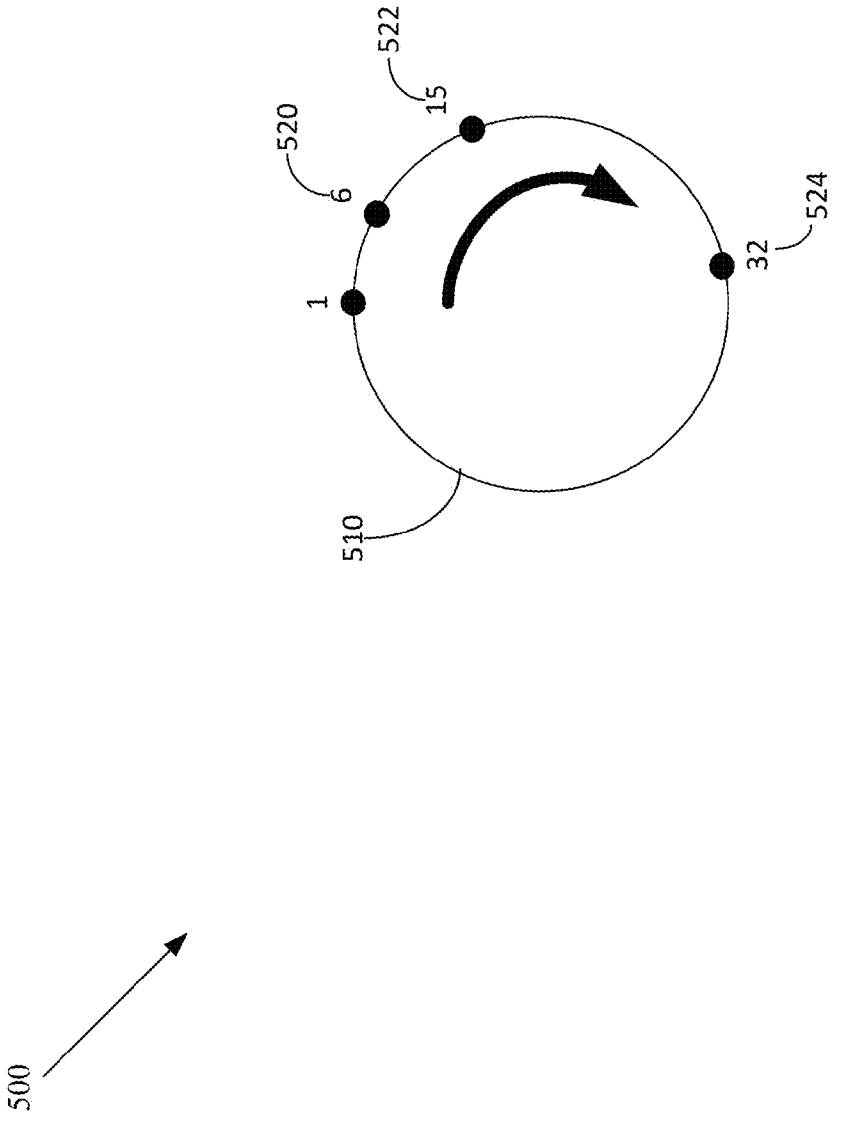


Fig. 5

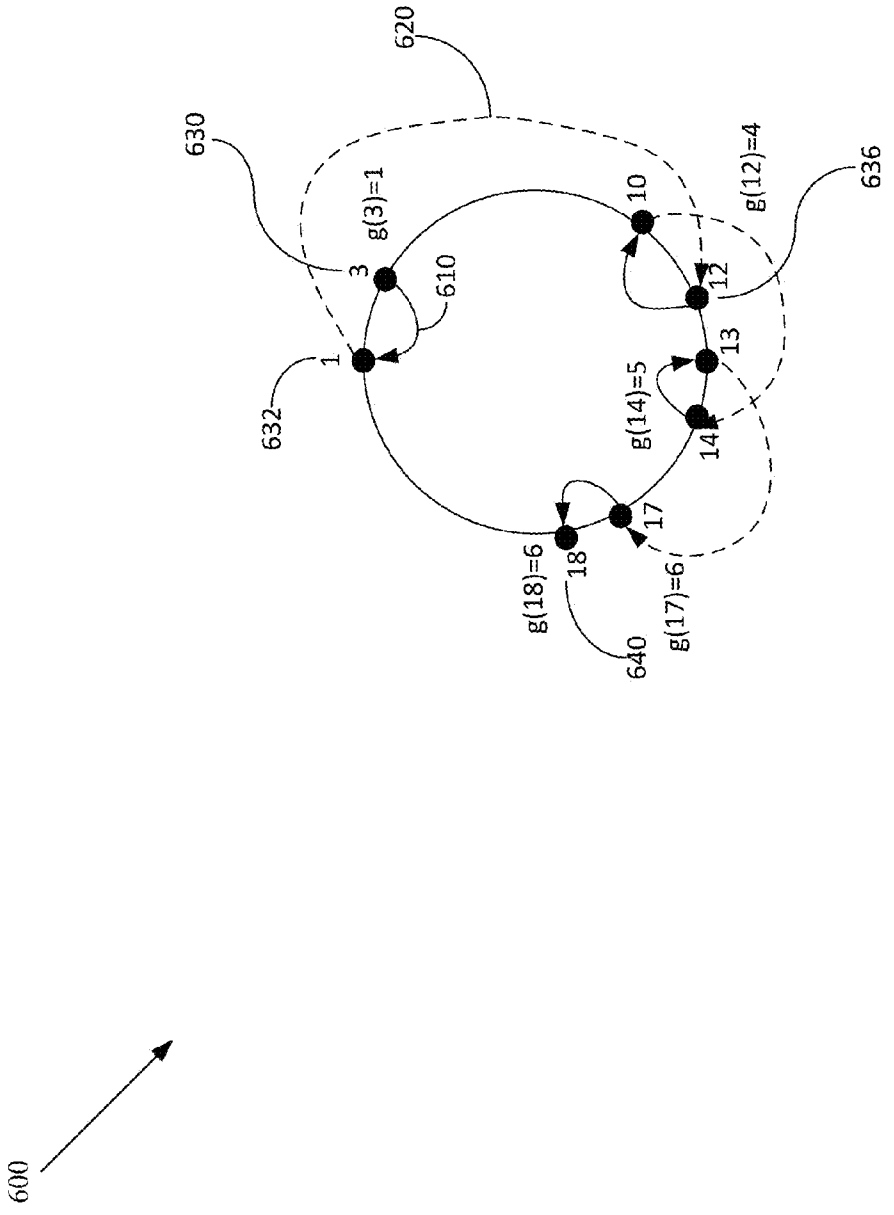

600
620
630
632
636
640
610
g(3)=1
g(12)=4
g(14)=5
g(18)=6
g(17)=6
1
3
10
12
13
14
17
18

Fig. 6

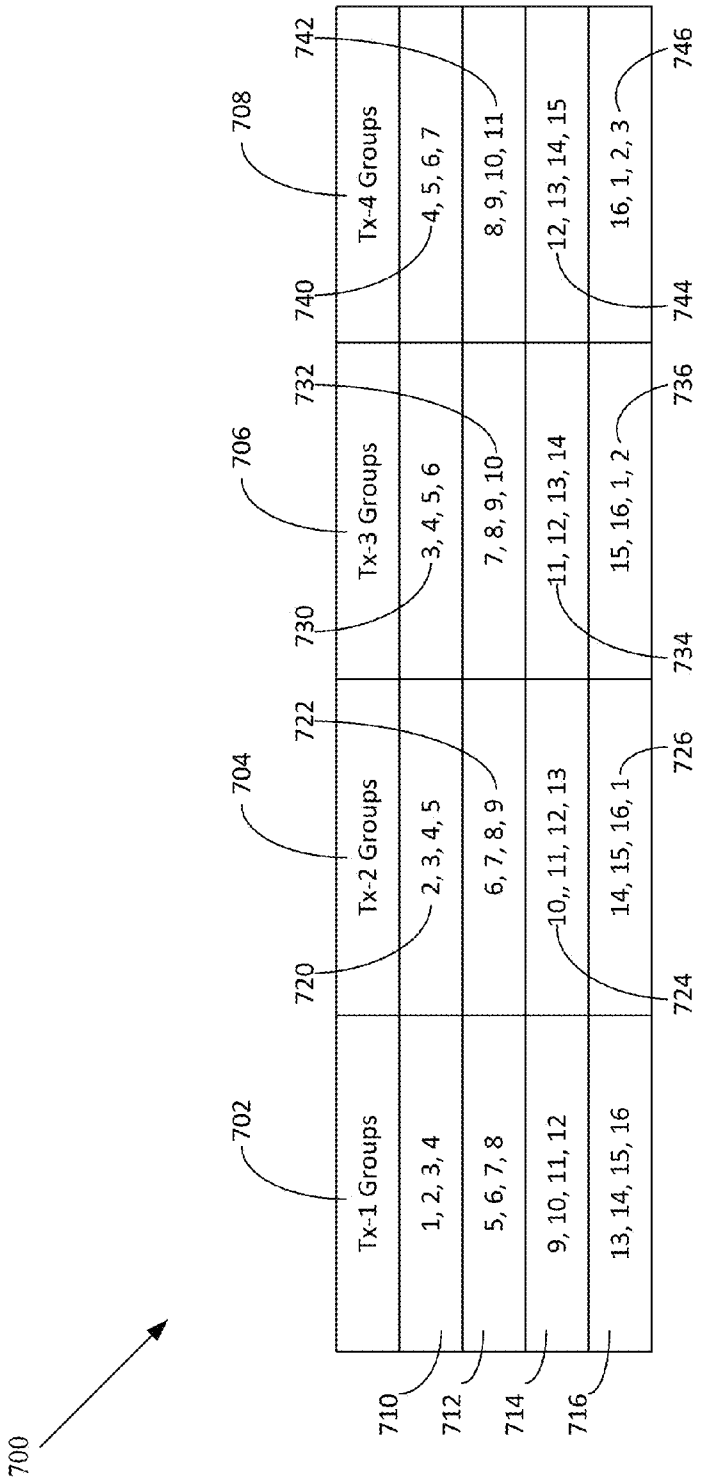

700
702
Tx-1 Groups
1, 2, 3, 4
5, 6, 7, 8
9, 10, 11, 12
13, 14, 15, 16
704
Tx-2 Groups
2, 3, 4, 5
6, 7, 8, 9
10,, 11, 12, 13
14, 15, 16, 1
706
Tx-3 Groups
3, 4, 5, 6
7, 8, 9, 10
11, 12, 13, 14
15, 16, 1, 2
708
Tx-4 Groups
4, 5, 6, 7
8, 9, 10, 11
12, 13, 14, 15
16, 1, 2, 3
710
712
714
716
720
722
724
726
730
732
734
736
740
742
744
746

Fig. 7

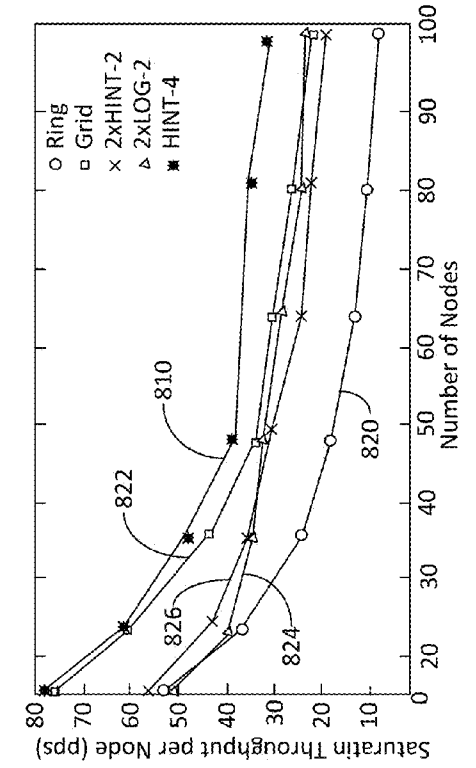

800
Saturatin Throughput per Node (pps)
Number of Nodes
Ring
Grid
2xHINT-2
2xLOG-2
HINT-4
810
820
822
824
826

Fig. 8a

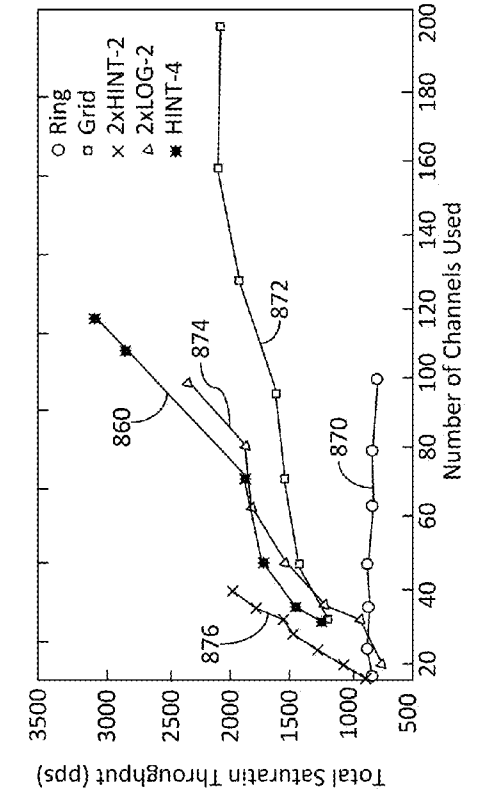

850
Total Saturatin Throughput (pps)
Number of Channels Used
Ring
Grid
2xHINT-2
2xLOG-2
HINT-4
860
870
872
874
876

Fig. 8b

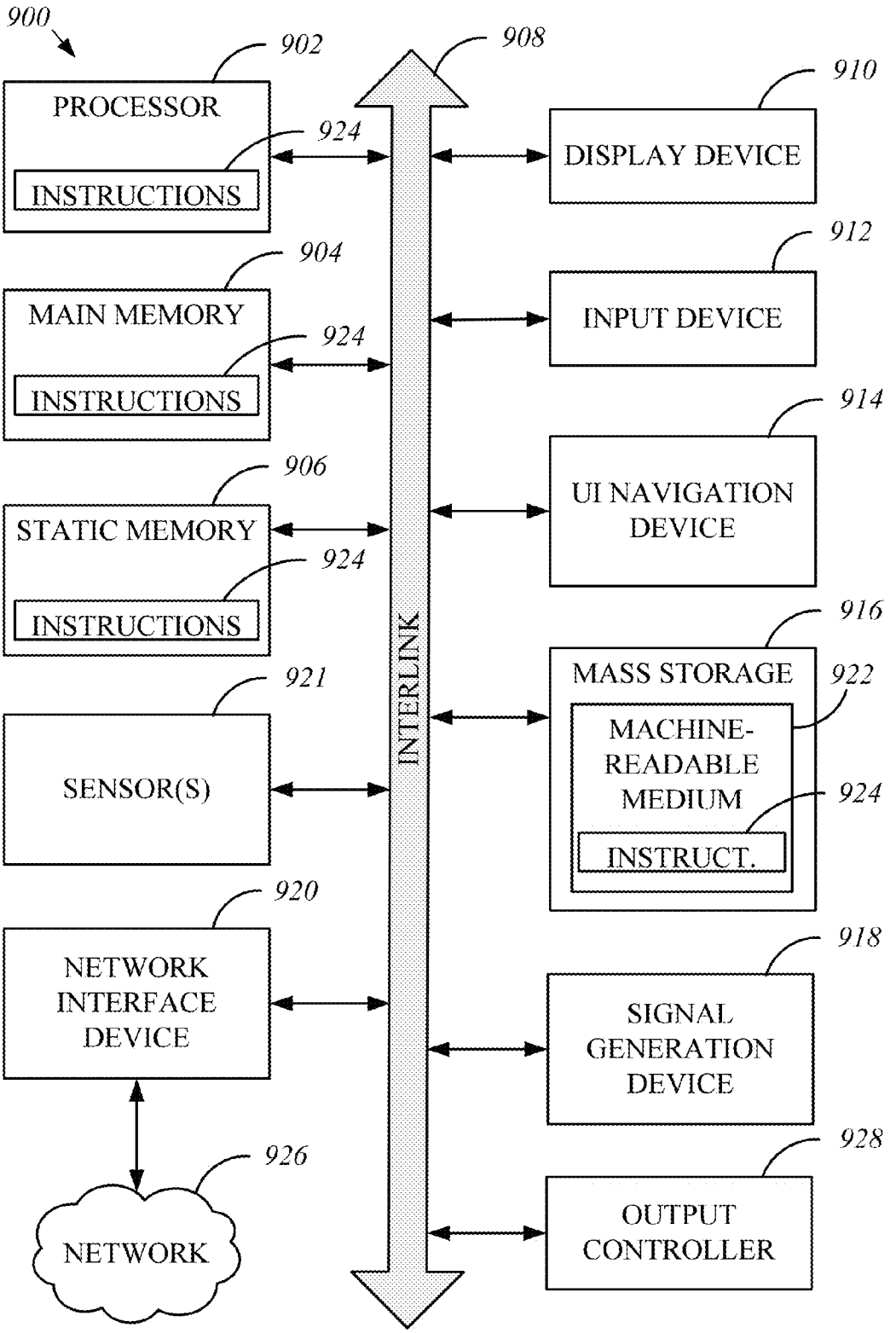

900
902
PROCESSOR
924
INSTRUCTIONS
904
MAIN MEMORY
924
INSTRUCTIONS
906
STATIC MEMORY
924
INSTRUCTIONS
921
SENSOR(S)
920
NETWORK INTERFACE DEVICE
926
NETWORK
908
INTERLINK
910
DISPLAY DEVICE
912
INPUT DEVICE
914
UI NAVIGATION DEVICE
916
MASS STORAGE
922
MACHINE-READABLE MEDIUM
924
INSTRUCT.
918
SIGNAL GENERATION DEVICE
928
OUTPUT CONTROLLER

Fig. 9

CHANNEL ASSIGNMENT PROCESSES FOR HIGH DENSITY MULTI-CHANNEL MULTI-RADIO (MC-MR) WIRELESS NETWORKS

CLAIM OF PRIORITY

[0001] This application claims the benefit of priority to U.S. Provisional Application Ser. No. 61/811,630, filed Apr. 12, 2013, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] There has been a lot of research on studying optimal scaling laws for wireless ad hoc networks under different assumptions about node capabilities, availability of infrastructure support, mobility, channel models, traffic models, etc. One practical way to improve the capacity of wireless ad hoc networks is to deploy multi-channel multi-radio (MC-MR) networks. The resulting capacity gains are mainly due to the use of additional channels as compared to the single channel model. This has attracted much attention recently and several works study the problem of channel assignment, routing, and scheduling in general MC-MR networks under different constraints. Scaling laws have been developed for general MC-MR networks. However, depending on the number of interfaces per node and the number of available channels, there can be a degradation in the network capacity.

[0003] Much of this work on scaling laws has focused on general ad hoc networks where it is assumed that the nodes are randomly distributed in an area and that multi-hop routing is used for end-to-end communication. However, one scenario that has received little attention involves the situation where nodes are within the transmission range of each other. This scenario is encountered in many real-life settings. Examples include students in a lecture hall, delegates attending a conference, or a platoon of soldiers in a battlefield.

[0004] A parking lot network configuration is popular for evaluating proposed network schemes. The parking lot network derives its name from parking lots, which include several parking areas connected via a single exit path. One issue with high-density multi-channel multi-radio (MC-MR) wireless networks is throughput. Processes for providing channel assignments do not address efficiency and throughput used for today's communication.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. **1** illustrates three channel assignments for parking lot networks;

[0006] FIG. **2** illustrates a channel assignment for a network of N=16 nodes using channels f_1 to f_8;

[0007] FIG. **3** shows the HINT-3 (Hierarchical Interleaved Channel Assignment—with 3 transceivers) assignment for a network of nodes with T=3 transceivers per node;

[0008] FIG. **4** shows channel assignments for a network of nodes with T=2 according to an embodiment;

[0009] FIG. **5** illustrates the formation of Tx-2 groups under LOG-2 according to an embodiment;

[0010] FIG. **6** illustrates the routing strategy under LOG-2 according to an embodiment;

[0011] FIG. **7** illustrates a channel assignment under RING for N=16;

[0012] FIG. **8***a* illustrates the plots the per node saturation throughput (in packets/sec, pps) vs. N;

[0013] FIG. **8***b* illustrates the plots of the total network saturation throughput vs. the number of channels used under each process according to an embodiment; and

[0014] FIG. **9** illustrates a block diagram of an example machine for providing efficient wideband inverse channelization for direct digital synthesizer based jamming techniques according to an embodiment.

DETAILED DESCRIPTION

[0015] The following description and the drawings sufficiently illustrate specific embodiments to enable those skilled in the art to practice them. Other embodiments may incorporate structural, logical, electrical, process, and other changes. Portions and features of some embodiments may be included in, or substituted for, those of other embodiments. Embodiments set forth in the claims encompass available equivalents of those claims.

[0016] According to an embodiment, optimal channel assignment, routing, and scheduling in an MC-MR parking lot network are considered to maximize the uniform per node throughput. Further, the scaling behavior of per node throughput as a function of network size is characterized. Static channel assignment algorithms are used, where a particular assignment, once assigned, is used for a reasonably long period of time, which is influenced by the practical limitations and resulting overheads associated with dynamic channel switching. In this setting, there is rich design space involving the number of available channels, number of transceivers per node and the network size. According to an embodiment, a class of algorithms are parameterized by T, the number of transceivers per node, that can achieve

$$\Theta\left(\frac{1}{N^{1/T}}\right)$$

per node throughput using $\Theta(TN^{1-T})$ channels in the parking lot model. Thus, a method in this class can achieve $\Theta(1)$ per node throughput if $T=\Theta(\log_2 N)$. In view of practical constraints on T, another method that can achieve

$$\Theta\left(\frac{1}{(\log_2 N)^2}\right)$$

per node throughput using two transceivers per node. A fundamental relationship exists between the network size, the total number of channels used, and the achievable per node throughput under any strategy. Methods according to embodiments described herein achieve close to optimal performance at different operating points of this fundamental bound.

[0017] The parking lot model is not very interesting when considering single-channel wireless networks because in this case there is one feasible solution. To ensure connectivity, transceivers may use the same channel. This results in equipped with multiple transceivers and the network has multiple available channels, the problem of channel assignment to different transceivers to maximize per node throughput becomes non-trivial. In this case, to increase network capacity, the transceivers may be assigned to different channels. This can result in a network graph that effectively has a multi-hop topology even though nodes are within each oth-

er's transmission range and could reach each other in one hop if they were using the same channel. Further, by choosing different assignments, a variety of such effective network topologies can be formed.

[0018] FIG. **1** illustrates three channel assignments for parking lot networks **100**. Each of the networks **100** includes eight nodes **110** with two transceivers **120**, **122** per node. The tables **130** **132**, **134** associated with each channel assignments show a list of nodes that share an orthogonal channel for the transceiver. For example, nodes 1-8 **110** use first transceiver **120** arranged in 4 channels **150**, **152**, **154**, **156**. The second transceiver **122** of nodes 1-8 **112** are arranged in a manner to minimize hops to any other node.

[0019] For each transceiver, Tx-1 **120** and Tx-2 **122**, the entries in the tables **130**, **132**, **134** show the list of nodes that share an orthogonal channel on that transceiver. For each transceiver (Tx-1 and Tx-2), the entries in the tables show the list of nodes that share an orthogonal channel on that transceiver. The resulting effective topologies **160**, **162**, **164** are shown on the right. These are only three out of many possible channel assignments for network topologies.

[0020] In FIG. **1**, the presence of multiple transceivers **130**, **132** adds a "degree of freedom" and expands the network design space considerably. The problem of throughput maximization involves a joint optimization of the channel assignment, routing, and scheduling strategies. This leads to a tradeoff, wherein given a fixed number of transceivers per node, a channel assignment scheme uses more channels and allows for more concurrent transmissions. However, the path between any two nodes **110** tends to become longer, leading to more relay transmissions and reduced per node throughput. To keep the path lengths small, more of the nodes **110** may share a channel. However, this reduces throughput as at most one of node **110** may transmit per channel at any time because spatial reuse of frequency channels is not possible in the parking lot model.

[0021] Thus, the number of concurrent transmissions is to be maximized while keeping the path lengths small. However, this by itself is not sufficient. For example, the first transceiver **120** of nodes **110** may be assigned to the same channel and form many small groups using the remaining transceivers. With this assignment, nodes are within one hop of each other while many concurrent transmissions are possible. However, the common channel of the first transceiver becomes a bottleneck. Sufficient capacity for flows in the network is to be provided.

[0022] A network model is based on a channel model, a traffic model and a channel assignment model. The channel model may include a wireless network of N nodes, indexed 1, 2, . . . , N, where nodes are within the transmission range of each other. The network may have a total of F orthogonal frequency channels **150-156**, each of bandwidth B Hz. Every node in the network may have the number, T, transceivers **120**, **122**≥2. Each transceiver **120**, **122** may be assigned at most one channel at any time. Transceivers **120**, **122** may operate in the half-duplex mode wherein the transceivers **120**, **122** may transmit or receive (but not both) on a channel **150-156** at any time, and a collision model for interference allows at most one transceiver **120**, **122** transmitting successfully on a channel **150-156** at any time. The link level transmission rate per channel **150-156** may be the same for channels **150-156** and is given by R bps.

[0023] For a traffic model, an N source-destination pair random unicast model may be used, where every node is the source of one unicast session destined to another node that is chosen uniformly at random. Each source may generate packets of size D bits at a rate given by λ packets/sec. The source-destination pairings are not known a priori. If the pairings were known, then the channel assignments and routing with respect to them may be optimized. This would yield higher per node throughput. However, the traffic patterns are not known a priori and/or change rapidly. Under these conditions, the traffic model is equivalent to the model where each of nodes 1-8 **140** generates packets at rate λ packets/sec and each packet is equally likely to be destined to any other node. According to an embodiment, the rate, λ, that can be supported is maximized and this rate may be referred to as the uniform per node throughput.

[0024] For a channel assignment model, static channel assignment schemes are used, where a particular assignment, once assigned, is used for a reasonably long period of time. Dynamic channel assignment may be shown to outperform static schemes. Indeed, it may be shown to achieve the best possible throughput. However, factors such as switching delay, coordination overheads, and hardware constraints make dynamic channel assignment challenging to implement in practice.

[0025] Given the network model based on the above-described channel model, traffic model and channel assignment model, the uniform per node throughput may be maximized. Since the channel assignments under such a policy may effectively create a multi-hop topology, the overall policy includes the channel assignment, routing and transmission scheduling processes. For any given tuple, (N, T, F), this can be formulated as an optimization problem that searches over possible channel assignment, routing, and scheduling options and yields the maximum throughput. However, given the enormous search space, this approach quickly becomes intractable and does not yield useful insights.

[0026] Instead, a scaling analysis approach may be used, where the scaling behavior of the achievable throughput is characterized as a function of the network size N. This approach, while being tractable, provides insights into the optimal network design and helps derive scaling laws. In analyzing the scaling behavior of the throughput, the number of available channels, F, may scale with the number of nodes, N, according to a fixed function. For example, F(N) may be $\sqrt{N}$. This approach significantly simplifies the problem and allows the development of processes with achievable throughput that may be computed exactly in closed form. For simplicity, transmission rates are normalized and idealized so that 1 packet may be transmitted per channel use.

[0027] An embodiment described herein includes HINT-T (Hierarchical Interleaved Channel Assignment—with T transceivers), which is a class of channel assignment strategies that may achieve

$$\Theta\left(\frac{1}{N^{1/T}}\right)$$

per node throughput using

$$F = \Theta\left(N^{\frac{T-1}{T}}\right)$$

channels and T transceivers per node. The process is based on forming

$$N^{\frac{T-1}{T}}$$

groups, each of size $N^{1/N}$, for every transceiver index. Then, transceivers **120**, **122** are assigned to these groups in such a way that each of nodes 1-8 **140** may reach every other node in at most T hops. For simplicity of presentation, $N^{1/T}$ will be an integer. However, embodiments described herein may be modified to be applicable when $N^{1/T}$ is not an integer. However, for brevity, this extension is not described herein.

[0028] FIG. **2** illustrates a channel assignment **200** for a network of N=16 nodes using channels f_1 to f_8. Nodes in the second transceiver group **222**, Tx-2, may be obtained by interleaving nodes from the Tx-1 groups **220**. As shown herein below, the same idea can be applied in a hierarchical fashion to obtain assignments for the general T case. Hence, this family of schemes may be referred to as HINT-T: Hierarchical Interleaved Channel Assignment with T transceivers.

[0029] Here, T may be equal to 2 and $M=N^{1/2}$. The first transceivers may be grouped into M groups **250-256**, each containing M nodes **260**, **262**, **264**, **266**. These may be referred to as the Tx-1 groups **220** and consecutively numbered nodes **260-266** may be assigned to each group. For example, the first transceiver group **220**, Tx-1, contains nodes 1, 2, . . . , M, the second transceiver groups **222**, Tx-2 contain nodes M+1, M+2, . . . , 2M, etc.

[0030] Each of the transceiver groups **220**, **222** thus formed is assigned an orthogonal channel. Since there are a total of 2M groups **250-256**, **270-276**, the total number of channels used is 2M.

[0031] The scheduling and routing strategy that is used with this assignment will now be described. For a scheduling strategy, every transceiver **220**, **222** in a group **250-256**, **270-276**, respectively, gets the same fraction of time to transmit on that group's channel. Since each group has M nodes with each having M transceivers, every transceiver in the group gets 1/M of the total transmission capacity of the channel.

[0032] For a routing strategy, if a destination node d is in the same Tx-1 group **220**, **222**, for any source node s, the source node transmits directly to d in one hop on its Tx-1 channel. Else, s transmits to node r in its Tx-2 group which shares its Tx-1 group with d. Node r then forwards to d using its Tx-1 channel.

[0033] For example, in FIG. **2**, the route from node 1 **260** to node 3 **264** follows the path 1-3 on channel f_1 **202**. This involves transmissions by the first transceiver of node 1. On the other hand, the route from node 1 **260**/**280** to node 11 **268**, **269** follows the path from node 1 **280** to node 9 **284** on channel f_5 **204** and from node 9 **271** to node 11 **268** on channel f_3 **206**. This involves transmissions by the second transceiver **222** of node 1 **280** and the first transceiver **220** of node 271. It can be seen that this routing strategy ensures that every node is within 2 hops of any other node.

[0034] The HINT-2 assignment along with the scheduling and routing strategy as described above may be used to achieve a throughput of 1/M for every node. For $N^{1/2}=M$ (where M is an integer), HINT-2 can achieve a uniform per node throughput of $1/N^{1/2}$ using $2N^{1/2}$ channels. Because of the symmetry of the assignment, it is sufficient to focus on the total load on each of the two transceivers **220**, **222** of node 1 **260**, **280** and show that it can be supported. Considering the second transceiver **222** of node 1 **280**, node 1 **280** transmits packets generated by itself that are destined for nodes in Tx-1 groups **250-256** other than its own group. There are M−1 such groups and each group has M nodes. Node 1 **260**, **280** generates packets at rate

$$\frac{\lambda}{N-1}$$

for each of these nodes. Thus, the total traffic load on the second transceiver **222** of node 1 **280** is given by

$$\frac{\lambda M(M-1)}{N-1}.$$

This may be less than the total transmission rate 1/M. Solving this provides:

$$\lambda \le \frac{N-1}{M^2(M-1)} = \frac{M^2-1}{M^2(M-1)} = \frac{1}{M} + \frac{1}{M^2} \quad (1)$$

[0035] From this, it can be seen that $\lambda=1/M$ satisfies equation 1 above. A similar result may be shown for the first transceiver **220** of node 1 **260**. Since HINT-2 uses 2M channels and $M=N^{1/2}$.

[0036] For T>2, let $M=N^{1/T}$. Similar to the T=2 case, the HINT-T strategy forms M^{T-1} groups for every transceiver index. To generalize, the groups corresponding to transceiver index k are called Tx-k groups where $1\le k\le T$. Each Tx-k group contains M nodes and is assigned one orthogonal channel. Since there are a total of TM^{T-1} such groups, the total number of channels used under HINT-T is TM^{T-1}. The node assignment to these groups is performed as follows.

[0037] Fix a transceiver index k where $1\le k\le T$. Let i and j be integers such that $1\le i\le M^{T-k}$ and $1\le j\le M^{k-1}$. Then the Tx-k group number $(i-1)M^{k-1}+j$ contains the following nodes:

$$\{(i-1)M^k+j,(i-1)M^k+j+M^{k-1},$$

$$(i-1)M^k+j+2M^{k-1},(i-1)M^k+j+3M^{k-1},\ldots$$

$$(i-1)M^k+j+(M-1)M^{k-1}\}. \quad (2)$$

[0038] This definition ensures that every Tx-k group has M nodes. Further, the total number of Tx-k groups is $\Sigma_{i=1}^{M^{T-k}}\Sigma_{j=1}^{M^{k-1}}1=M^{T-1}$.

[0039] FIG. **3** shows the HINT-3 assignment **300** for a network of N=27 nodes **310** with T=3 transceivers **320**, **322**, **324** per node. In general, the HINT-T assignment **300** ensures that every node is within T hops of any other node.

[0040] In order to describe the routing strategy, the following collection of sets are defined for each transceiver index k where $1\le k\le T$. For $1\le i\le M^{T-k}$, S_{ik} is defined as the set containing the nodes $(i-1)M^k+1$ to iM^k. For each k, there are M^{T-k} such sets, each containing M^k consecutively numbered nodes. These may be referred to as the "level k sets." FIG. **3** illustrates these sets for N=27 **310**. Note that for k=3 **320**, **322**, **324**, there is one such set S_{13} **330** and it includes all nodes.

[0041] The following properties follow directly from the definition of the level sets and the HINT-T assignment in equation 2.

[0042] Any two level sets S_{ik} and S_{jk} where i≠j are disjoint.

[0043] Any level set S_{ik} where k>1 is a union of M level sets from level k−1.

[0044] Under the HINT-T assignment from equation 2, for 1≤k≤T−1, no two nodes from any S_{ik} are in the same Tx-k+1 group.

[0045] To illustrate the third property in FIG. **3**, note that nodes 1-3 **310** from the first Tx-1 group **320** are in different Tx-2 groups **322**, i.e., s_{11} s_{21}, s_{31}. Similarly, nodes 3, 6, 9 **342** from the third Tx-2 group **322** are in different Tx-3 groups s_{31}, s_{71}, s_{91}. This is precisely the interleaving of nodes from lower Tx groups to form upper Tx groups as seen in HINT-2. HINT-T generalizes this interleaving to T hierarchical levels.

[0046] Next, the scheduling and routing strategy that is used with HINT-T is described. For a scheduling strategy, every transceiver in a group gets 1/M of the total transmission capacity of the channel, which is similar to HINT-2 strategy. For a routing strategy, k(a, b) is defined, for any two nodes a and b, as the smallest k for which there exists a level set S_{ik} such that both a and b are in S_{ik}. Note that at least one such set exists since the set S_{1T} contains all nodes. Further, k(a, b)≤T for all a, b. The routing strategy from a source node s to a destination node d can be described using these k(a, b) values.

[0047] First, k(s, d) is calculated. If k(s, d)=1, then d is in the same Tx-1 group as s, and s transmits directly to d in one hop using its first transceiver. If k(s, d)≠1, then d is in a different Tx-1 group than s. If d is in the same Tx-k (s, d) group as s, then s transmits directly to d in one hop using its k(s, d)th transceiver.

[0048] Else, S determines the node with the smallest value of k(r, d) among its neighbors r in its Tx-k(s, d) group. This node is denoted by r*. Then s relays the packet to node r* using its k(s, d)th transceiver. Node r* now uses the same algorithm as described before to route the packet to d.

[0049] Accordingly, in FIG. **3**, where node 25 wants to send to node 14. A calculation of k(25, 14) is performed. Using FIG. **3**, it can be seen that S_{13} **330** is the only set that has both nodes 25 and 14. Thus, we have that k(25, 14)=3. Next, since 14 is not a neighbor of node 25 **350** in node 25's Tx-3 group **356**, node 25 calculates k(7,14) and k(16, 14) for its Tx-3 group **324** neighbors 7 **352** and 16 **354**. Using FIG. **3**, k(7, 14)=3 and k(16, 14)=2. Therefore, node 25 **350** forwards the packet to node 16 **354** for relaying to the destination. This procedure is now repeated by node 16 **354**, where node 16 **360** uses the second transceiver **322** to transmit to node 13 **362** in its Tx-2 group **322**. From there, node 13 **370** uses its first transceiver in transmitter group **320** to transmit to node 14 **372** in its Tx-1 group **320**.

[0050] The HINT-T routing strategy ensures that there are at most T hops between any pair of nodes. Given any set S_{ik}, a node a ∈ Sik may reach any other node b ∈ S_{ik} in at most k hops using the HINT-T routing strategy and the level set S_{1T} contains all nodes.

[0051] The HINT-T assignment along with the scheduling and routing strategy as described above may achieve a throughput of 1/M for every node. For $N^{1/T}$=M (where M is an integer), HINT-T achieves a uniform per node throughput of $1/N^{1/T}$ using TN_T^{T-1} channels. This implies that, if T=$\log_2$ N and if there are N $\log_2$ N/2 channels available, then HINT-T can achieve a per node throughput given by $1/N^{1/\log_2}$. Thus, it is possible to get Θ(1) per node throughput if each node has $\log_2$ N transceivers and there are N $\log_2$ N/2 channels available. This is in sharp contrast to the case of a single radio network, i.e., T=1. Note that the best possible uniform throughput for T=1 under static channel assignment is 1/N. This is because when T=1, transceivers may share the same channel so that the network remains connected. However, when T>1, much higher throughput can be achieved. This shows that there is a fundamental difference between single radio and multi radio networks when static channel assignment is used.

[0052] However, requiring Θ($\log_2$ N) transceivers per node may be impractical. The availability of Θ(N $\log_2$ N/2) channels may also be impractical.

[0053] This raises the question of whether the number of transceivers per node and total channels to be used to grow to infinity to get θ(1) per node throughput. Further, there is a question of whether there a fundamental way to characterize the performance of any channel assignment strategy. Specifically, the relationship between number of transceivers, number of channels used, network size and per node throughput are to be determined.

[0054] FIG. **4** shows channel assignments **400** for a network of N−24−8 $\log_2$8 nodes with T=2 according to an embodiment.

[0055] According to another embodiment,

$$\Theta\left(\frac{1}{(\log_2 N)^2}\right)$$

throughput per node may be achieved with two transceivers per node using

$$\theta\left(\frac{N}{\log_2 N}\right)$$

channels using a LOG-2 process. The main idea behind this process is to first form two sets of groups, one per transceiver index **420**, **422**. Each set contains

$$\theta\left(\frac{N}{\log_2 N}\right)$$

groups **430-444**, wherein each group has size θ($\log_2$ N) nodes. Then, the strategy assigns nodes to these groups in such a way that a node can reach any other node in at most θ($\log_2$ N) hops. For simplicity of presentation, N is of the form N=M $\log_2$ M where $\log_2 M \in Z^+$. However, this process may be modified to be applicable when this is not the case.

[0056] The channel assignment is performed by first grouping the first transceiver of all nodes into M Tx-1 groups **430-444**, wherein each contains $\log_2$ M consecutively numbered nodes. Thus, the kth Tx-1 group contains nodes (k−1) $\log_2$ M+1, (k−1) $\log_2$ M+2, . . . , k $\log_2$ M.

[0057] Next, the second transceiver of all nodes is grouped into M Tx-2 groups **450-464**, each containing $\log_2$ M nodes. Nodes are assigned as follows. For 1≤i≤$\log_2$ M, the ith node from Tx-1 group number ((j−1+2^{i-1}) mod M) is assigned to be the ith node of Tx-2 group number j (where 1≤j≤M). The "mod

M" operation used here and in rest of the paper is defined, for any non-negative integers a and b, using use the following definition:

$$(a \bmod M) \triangleq \begin{cases} M & \text{if } a = bM \\ x \text{ if } a = bM + x & \text{where } 0 < x < M \end{cases}.$$

[0058] Each of the groups thus formed is assigned an orthogonal channel. Since there are a total of 2M groups, the total number of channels used is 2M.

[0059] To illustrate the working of the algorithm, consider Tx-2 group number 7 **462**. For $1 \le i \le 3$, the i^{th} node from Tx-1 group number $((7-1+2^{i-1}) \bmod 8)$ is assigned to be the node of this group. For i=1, this is given by the first node of Tx-1 group (6+1 mod 8)=7, i.e., node 19 **480**. For i=2, this is given by the second node of Tx-1 group (6+2 mod 8)=8, i.e., node 23 **482**. For i=3, this is given by the third node of Tx-1 group (6+4 mod 8)=2, i.e., node 6 **484**.

[0060] In any Tx-2 group number j, there is one node from each of the Tx-1 groups numbered ((j−1+2i−1) mod M) where $1 \le i \le \log 2$ M. This means that the difference between the Tx-1 group numbers of consecutive nodes in a Tx-2 group follows the geometric sequence $2^0, 2^1, 2^2, \ldots 2^{i-1}$ where $1 \le i < \log_2 M$.

[0061] FIG. **5** illustrates the formation of Tx-2 groups under logarithmic with two transceivers (LOG-2) **500** according to an embodiment. Nodes in the first Tx-2 group under LOG-2 assignment for N=64 are placed on a ring **510**. It can be seen that the neighboring nodes of node 1, i.e., node 6 **520**, node 15 **522** and node 32 **524**, are located progressively farther away as traversing clockwise on the ring **510**. The assignment on Tx-1 ensures that node 1 **510** may reach close by nodes 2, 3, 4 (not shown) in one hop. Using a combination of local neighbors on Tx-1 and progressively farther away neighbors on Tx-2, a node is within $2 \log_2 M+1$ hops of any other node, much like the use of distributed hash tables for fast lookups.

[0062] A routing strategy according to an embodiment is based on the following collection of sets for each Tx-2 group j (where $1 \le j \le M$). For every i^{th} node in this group. A set $u_{i,j}$ is defined as follows. For $1 \le i \le \log_2 M-1$, $u_{i,j}$ contains 2^{i-1} Tx-1 group numbers, starting from $((j-1+2^{i-1}) \bmod M)$ and incrementing by 1 and using the "mod M" operation as defined earlier. For $i=\log_2 M$, $u_{i,j}$ contains $(2^{i-1}+1)$ Tx-1 group numbers, starting from $((j-1+2^{i-1}) \bmod M)$ and incrementing by 1 while using the mod M operation. For example, for the network in FIG. **4**:

$$u_{11}=\{1\}, u_{21}=\{2,3\}, u_{31}=\{4,5,6,7,8\}$$

$$u_{17}=\{7\}, u_{27}=\{8,1\}, u_{37}=\{2,3,4,5,6\}$$

[0063] There are a total of M $\log_2$ M such sets. These sets are used for the following routing strategy.

[0064] A node at the i^{th} level of Tx-2 group j is responsible for relaying to nodes in those Tx-1 groups whose index is in the set $u_{i,j}$. Thus, this set lists those Tx-1 groups that are "covered" by this node. Hence, it is called a Cover Set. For example, in FIG. **4**, node 5 **490** which is at the 2^{nd} level in Tx-2 group 1 **450** forwards data for destinations in the set of Tx-1 groups in u_{21}. Likewise, node 6 **484**, which is at the 3^{rd} level in Tx-2 group **7462** forwards data for destinations in the Tx-1 groups of u_{37}. For any 3, the sets $u_{i,j}$ are disjoint and their union covers Tx-1 groups **420**.

[0065] The scheduling strategy under LOG-2 provides every transceiver in a Tx-1 group **420** the same fraction of time to transmit on that group's channel. However, the first node gets the transmission time in a Tx-2 group **422**. However, the routing strategy of LOG-2 may use the first node of each Tx-2 group **422** to transmit on that group's channel.

[0066] The routing strategy under LOG-2 involves a node n that has a packet destined for node m. This packet could have been generated by node n itself, or it could have been forwarded to n to be relayed to m. If the Tx-1 group number of nodes n and m be g(n) and g(m) respectively, then to route a packet from n to m, n first checks if m is in its Tx-1 group, i.e., if g(n)=g(m). If yes, then n transmits directly to m in one hop using its first transceiver. Else, n transmits the packet to the first node in Tx-1 group number g(n) for relaying to n. This step is not used if n itself is the first node in its Tx-1 group.

[0067] Let q be the first node in Tx-1 group g(n). Under LOG-2, q will also be the first node in Tx-2 group g(n). Node q checks if m is in its Tx-2 group. If yes, it transmits directly to m in one hop using its second transceiver. Else, node q transmits the packet to that node in its Tx-2 group that "covers" node m. More precisely, q transmits to the i^{th} node in its Tx-2 group for forwarding to m where $2 \le i \le \log_2 M$ and g(m) $\epsilon u_{i,g(n)}$This process is repeated until the packet gets delivered.

[0068] FIG. **6** illustrates the routing strategy under LOG-2 **600** according to an embodiment. In FIG. **6**, solid arrows **610** show transmissions in Tx-1 groups and dashed arrows **620** show transmissions in Tx-2 groups. FIG. **6** illustrates this procedure for the 24 node network **400** of FIG. **4**. In FIG. **6**, when node 3 **630** wants to send to node 18 **640**, g(3)=1 to node 1 **632** and g(18)=6 for node 18 **640**. Thus, node 3 **630** transmits the packet to node 1 **632** in its Tx-1 group for relaying to node 18 **640**. Node 1 **632** checks if node 18 **640** is in its Tx-2 group. Since node 18 **640** is not in its Tx-2 group, node 1 **632** determines the node in its Tx-2 group that covers node 18 **640**. This node is given by the third node, i.e., node 12 **636**, since $u_{31}=\{4,5,6,7,8\}$. Therefore, node 1 **632** transmits the packet to node 12 **636** in its Tx-2 group. Node 12 **636** now repeats this procedure. FIG. **6** shows the final outcome of this process, wherein the route is given by 3-1-12-10-14-13-17-18. The hops alternate between Tx-1 and Tx-2 group transmissions. Further, the first node of a Tx-2 group transmits in any Tx-2 group transmission.

[0069] The LOG-2 routing strategy ensures that there are at most $2 \log_2 N+1$ hops between any pair of nodes. This is based on the observation that, at each step in a Tx-2 transmission, the distance between the node holding the packet and the destination decreases by at least half.

[0070] The LOG-2 assignment along with the scheduling and routing strategy, as described above, may be used to achieve a throughput of $1/\log_2 M)^2$ for every node. For N=M$\log_2$ M, where log 2 M $\epsilon Z+$, LOG-2 can achieve a uniform per node throughput of $1/(\log_2 M)2$ using 2M channels. Because of the symmetry of the assignment, it is sufficient to focus on the total load on the nodes in the first Tx-1 group and the first Tx-2 group. Then, a bound on the total number of group-to-group traffic flows that involve these groups may be calculated. This is used to show that a per node input rate of $1/(\log_2 M)2$ is feasible.

[0071] LOG-2 may thus achieve a per node throughput of at least $1/(\log_2(N))^2$ with two transceivers per node. Therefore, a throughput close to $\Theta(1)$ per node may be obtained with $\Theta(1)$ transceivers per node. However, under the parking lot model, $\Omega(N)$ channels are used to get $\Theta(1)$ per node through-

put irrespective of the number of transceivers per node. However, given $\Omega(N)$ channels, achieving a throughput of $\Theta(1)$ per node throughput using $\Theta(1)$ transceivers per node under static channel assignment may not be possible.

[0072] π is used to denote the set of possible feasible policies for channel assignment, routing, and scheduling under the network model. A simple relation exists between the total number of channels used, network size, and maximum per node throughput achievable under any policy $p \in P$. C_p is used to denote the number of channels used by the channel assignment under p and $\bar{L}_p$ is used to denote the resulting average path length traversed by a packet under p. An average is taken over source-destination pairs. The maximum per node input rate that can be supported under p is λ_p. Then, since the total traffic load cannot exceed the total transmission capacity of the network:

$$N\lambda_p L_p \leq C_p. \tag{3}$$

[0073] The left hand side of equation (3) denotes the time average total number of transmissions to deliver packets from sources to destinations. This cannot exceed C_p, i.e., the maximum number of transmissions possible per unit time. Since $\bar{L}_p \geq 1$ under any p, it follows from equation (3) that $C_p=\lambda(N)$ when $\lambda=\Theta(1)$. Equation (3) is a condition for the feasibility of any input rate and can be used to establish a lower bound on the performance of any policy.

[0074] Then the efficiency of p, η_p for any channel assignment, routing, and scheduling policy $p \in \pi$ that uses C_p channels in a parking lot network of size N, a maximum per node input rate of λ_p may be supported. Then the efficiency of p, η_p is defined as:

$$\eta_p \triangleq \frac{N\lambda_p}{C_p}. \tag{4}$$

[0075] Since $\bar{L}_p \leq 1$ under any p, using equation (3) it follows that $\eta_p \leq 1$ for all $p \in P$. This includes the throughput maximizing policy obtained by solving the optimization problem for the tuple (N, T, C_p) Therefore, the maximum per node throughput achievable under a given policy p that uses C_p channels in a network of size N is within a factor η_p of the maximum per node throughput achievable under any policy that uses C_p channels on the same network. Thus, the efficiency of a policy establishes a lower bound on its performance.

[0076] Using the above results, the efficiency of the HINT-T and LOG-2 strategies can be calculated. Since HINT-T uses

$$TN^{\frac{T-1}{T}}$$

channels to support per node rate of

$$1/N^{\frac{1}{T}},$$

$\eta_{pHINT\text{-}T}$ is:

$$\eta_{HINT\text{-}T} = \frac{N}{N^{1/T} \times TN^{\frac{T-1}{T}}} = \frac{1}{T}. \tag{5}$$

[0077] For a fixed T, $\eta_{HINT\text{-}T}$ is independent of the network size N. Thus, HINT-T is within a constant factor of the optimal solution. Likewise, for $N=M \log_2 M$, LOG-2 uses 2M channels to support per node rate of $1/(\log_2 M)^2$, which yields:

$$\eta_{LOG\text{-}2} = \frac{N}{(\log_2 M)^2 2M} = \frac{1}{2\log_2 M} > \frac{1}{2\log_2 N} \tag{6}$$

[0078] Thus, the LOG-2 scheme is within a logarithmic (in network size) factor of the optimal solution. This may suggest that HINT-T has a better performance than LOG-2. However, for any given T, the maximum per node throughput under HINT-T is $1/N^{1/T}$, while LOG-2 can achieve at least $1/(\log_2 N)^2$ with $T=^2$, which exceeds $1/N^{1/T}$ for sufficiently large N.

[0079] Simulation-based results for a parking lot network with 4 transceivers per node compares

[0080] HINT-T and LOG-2 performance against two representative schemes referred to as RING and GRID.

[0081] FIG. **7** illustrates a channel assignment **700** under RING for N=16. The RING assignment scheme first forms N/4 Tx-1 groups **710-716** for Tx-1 **702**, each of size 4 and containing consecutively numbered nodes. The transceiver groups **720-726**, **730-736**, **740-746** for Tx-2 **704**, Tx-3 **706** and Tx-4 **708**, respectively, are obtained by shifting node IDs of each Tx-1 group **710-716** by 2, 3 and 4 with wraparound. The resulting topology resembles a ring (similar to Example 1 in FIG. **1**), hence the name. A GRID scheme places nodes in a 2-dimensional degree 4 torus grid and assigns a channel to each link in the resulting graph. Thus, each Tx group contains 2 nodes.

[0082] Under the RING assignment, it is easy to show that the average path length over source-destination pairs is $\Theta(N)$. Similarly, the total number of channels used is $N=\Theta(N)$. Thus, using equation (3), it follows that the maximum per node throughput under RING is $\Theta(1/N)$ and its efficiency is $\eta_{RING}=\Theta(\mathbf{1}/N)$. Under the GRID assignment, the average path length over source-destination pairs can be shown to be $\Theta(\sqrt{N})$ while the total number of channels used is $2N=\Theta(N)$. Thus, using equation (3), it follows that the maximum per node throughput under GRID is $\Theta(1/\sqrt{N})$. Further, using equation (4), its efficiency is $\eta_{GRiD}=\Theta(\mathbf{1}/\sqrt{N})$.

[0083] For the simulation, the input topology is a parking lot MC-MR network of size N nodes, where V is varied between 16 and 100. These nodes are placed in a 250 m×250 m in area and use a fixed transmit power such that nodes are within the transmission range of each other. Every node has 4 identical transceivers, each capable of operating on a channel of bandwidth 10 MHz assuming that such channels are available starting from 900 MHz. Each transceiver independently uses 802.11 CSMA for medium access on its assigned frequency channel. The raw MAC level throughput per channel is 1.2 Mbps.

[0084] Under each scheme, the assignments to the different transceivers are determined at the start of a simulation run and fixed for the duration of that run. In each run, traffic is gen-

erated using the uniform all-pair unicast model. Specifically, every node generates packets according to a Poisson process of fixed rate and each packet is equally likely to be destined to any of the other nodes. Packets are assumed to be fixed size user datagram protocol (UDP) packets of length 436 bytes that include control headers. Each simulation run has a duration of 150 seconds, wherein the total number of packets delivered successfully to their destinations is then counted. Default link state routing protocol available in optical networks for routing packets is used. Load balanced routing strategies under HINT and LOG, as discussed earlier, are not implemented. Thus, the achievable performance of HINT and LOG with load balanced routing is expected to outperform the results of the simulation.

[0085] The maximum achievable per node throughput under each scheme are to be compared. In addition, the results from the simulation may be compared against the theoretical bounds. Given a network size and an assignment scheme X, simulations were run with increasing values of the input rate until the total number of delivered packets does not increase anymore. This is referred to as the "saturation throughput" under X for a given N and it is used as a measure of the maximum per node achievable throughput under X for N. The theoretical bounds for maximum throughput are derived under idealized assumptions, such as collision free transmission scheduling, load balanced routing, no buffer overflows, and ignoring any control overheads (such as due to CSMA and link state routing updates). This no longer holds in the simulations, which are closer to the realistic setting. However, these factors affect the schemes being compared and the saturation throughput can be thought of as a measure of the remaining effective capacity.

[0086] Table 1 summarizes the theoretical performance bounds for RING, GRID, 2×HINT-2, 2×LOG-2, and HINT-4. The 2×HINT-2 process implements HINT-2 on transceivers 1, 2 and repeats it on transceivers 3, 4. Similarly, the 2×LOG-2 process implements LOG-2 on transceivers 1, 2 and repeats it on transceivers 3,4.

TABLE 1

	Process		
	λ_p	C_p	$\eta_p = \frac{N\lambda_p}{C_p}$
RING	$\Theta\left(\frac{1}{N}\right)$	$\Theta(N)$	$\Theta\left(\frac{1}{N}\right)$
GRID	$\Theta\left(\frac{1}{\sqrt{N}}\right)$	$\Theta(N)$	$\Theta\left(\frac{1}{\sqrt{N}}\right)$
2 × HINT-2	$\Theta\left(\frac{1}{\sqrt{N}}\right)$	$\Theta(\sqrt{N})$	$\Theta(1)$
2 × LOG-2	$\Theta\left(\frac{1}{(\log_2 N)^2}\right)$	$\Theta\left(\frac{N}{\log_2 N}\right)$	$\Theta\left(\frac{1}{\log_2 N}\right)$
HINT-4	$\Theta\left(\frac{1}{N^{1/4}}\right)$	$\Theta(N^{3/4})$	$\Theta(1)$

[0087] The different processes are first compared in terms of their saturation throughput.

[0088] FIG. **8***a* illustrates the plots the per node saturation throughput (in packets/sec, pps) vs. N **800** according to an embodiment. As can be seen, HINT-4 **810** outperforms the RING scheme **820** by 200-300% for high tens of nodes, and outperforms its nearest rival GRID **822** by nearly 150% at N=100. The behavior of the curves is consistent with the theoretical bounds with RING **820** showing the largest drop as N increases. The per node throughput under 2×LOG-2 **824** scales as $\Theta(1/(\log_2 N)^2)$ which is the best scaling performance among these schemes. However, in the finite range of N considered here, HINT-4 **810** outperforms 2×LOG-2 **824**. Both GRID **822** and 2×HINT-2 **826** also outperform 2×LOG-2 **824** up to a crossover point, after which 2×LOG-2 **824** is better. Eventually, 2×LOG-2 **824** will outperform HINT-4 **810** as well after a sufficiently large N.

[0089] GRID **822** generally has a better performance than both 2×HINT-2 **826** and 2×LOG-2 **824**. However, this plot considers the per node saturation throughput and does not capture the total number of channels used. To incorporate this, the processes are next compared in terms of their efficiency.

[0090] FIG. **8***b* illustrates the plots of the total network saturation throughput vs. the number of channels used under each process **850** according to an embodiment. Recall that efficiency of a process is the ratio between maximum total network throughput and the total number of channels used. Thus, the slope of the performance curve for a process in FIG. **8***b* may be interpreted as its efficiency at that point. It can be seen that both 2×HINT-2 **876** and 2×LOG-2 **874** have much higher efficiency than GRID **872**. Further, this gap increases with N.

[0091] FIG. **8***b* also agrees quite well with the theoretical bounds. The 2×HINT-2 **876** and HINT-4 **860** processes both have a theoretical efficiency of $\Theta(1)$, i.e., independent of N (see Table 1). Their curves in FIG. **8***b* have a slope that does not decrease with N. On the other hand, RING **870** has an efficiency of $\Theta(1/N$ which goes to 0 as N increases. Its curve in FIG. **8***b* flattens to slope 0 quickly. GRID **872** has efficiency $\Theta(1/\sqrt{N})$. Its curve also flattens, but more slowly than RING. Finally, 2×LOG-2 **874** has efficiency $\Theta(1/\log_2 N)$ and its slope is even slower to flatten.

[0092] In terms of both per node throughput and efficiency, RING **870** has the worst performance. Intuitively, this is because under RING **870**, packets may traverse $\Theta(N)$ hops on average, resulting in a vast majority of traffic being relay traffic. GRID **872** improves upon RING **870** because the average distance between nodes is now$\Theta(\sqrt{N})$. It has similar scaling as HINT-2 **876** in terms of throughput but uses a lot more channels. Thus, it has poor efficiency. The HINT-T schemes have the best performance in terms of their efficiency, which does not depend on N. However, in terms of throughput, T may be large to remain close to $\Theta(1)$ as N increases. LOG-2 **874** may achieve this with just 2 transceivers. However, its efficiency is not as good as HINT-T. Thus, both HINT and LOG are order optimal or close to order optimal along one of the dimensions (throughput or efficiency).

[0093] Scaling laws imply that in a random ad hoc network, if individual transceivers may operate over channels of fixed bandwidth (that does not increase with N), then the best possible scaling is $\theta(\sqrt{N})$ even if the network has a large number of channels available and each node has multiple (but finite) transceivers. Previous strategies have suggested keeping the transmit power sufficiently low, just enough to ensure

connectivity, and then using multi-hop routing. The motivation behind reducing the transmit power is to maximize spatial reuse of the finite network bandwidth.

[0094] In contrast, according to embodiments described herein, the parking lot model provides significantly higher throughput when nodes have multiple transceivers and the number of available channels scales with the network size. Further, reducing power to maximize spatial reuse of frequency does not help. Rather, it is better to preserve the parking lot structure and use the available channels while keeping inter-node distance small in the resulting effective topology by careful channel assignment.

[0095] FIG. **9** illustrates a block diagram of an example machine **900** for providing efficient wideband inverse channelization for direct digital synthesizer based jamming techniques according to an embodiment upon which any one or more of the techniques (e.g., methodologies) discussed herein may perform. In alternative embodiments, the machine **900** may operate as a standalone device or may be connected (e.g., networked) to other machines. In a networked deployment, the machine **900** may operate in the capacity of a server machine and/or a client machine in server-client network environments. In an example, the machine **900** may act as a peer machine in peer-to-peer (P2P) (or other distributed) network environment. The machine **900** may be a personal computer (PC), a tablet PC, a set-top box (STB), a Personal Digital Assistant (PDA), a mobile telephone, a web appliance, a network router, switch or bridge, or any machine capable of executing instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein, such as cloud computing, software as a service (SaaS), other computer cluster configurations.

[0096] Examples, as described herein, may include, or may operate on, logic or a number of components, modules, or mechanisms. Modules are tangible entities (e.g., hardware) capable of performing specified operations and may be configured or arranged in a certain manner. In an example, circuits may be arranged (e.g., internally or with respect to external entities such as other circuits) in a specified manner as a module. In an example, at least a part of one or more computer systems (e.g., a standalone, client or server computer system) or one or more hardware processors **902** may be configured by firmware or software (e.g., instructions, an application portion, or an application) as a module that operates to perform specified operations. In an example, the software may reside on at least one machine readable medium. In an example, the software, when executed by the underlying hardware of the module, causes the hardware to perform the specified operations.

[0097] Accordingly, the term "module" is understood to encompass a tangible entity, be that an entity that is physically constructed, specifically configured (e.g., hardwired), or temporarily (e.g., transitorily) configured (e.g., programmed) to operate in a specified manner or to perform at least part of any operation described herein. Considering examples in which modules are temporarily configured, a module need not be instantiated at any one moment in time. For example, where the modules comprise a general-purpose hardware processor **902** configured using software; the general-purpose hardware processor may be configured as respective different modules at different times. Software may accordingly configure a hardware processor, for example, to constitute a particular module at one instance of time and to constitute a different module at a different instance of time. The term "application," or variants thereof, is used expansively herein to include routines, program modules, programs, components, and the like, and may be implemented on various system configurations, including single-processor or multiprocessor systems, microprocessor-based electronics, single-core or multi-core systems, combinations thereof, and the like. Thus, the term application may be used to refer to an embodiment of software or to hardware arranged to perform at least part of any operation described herein.

[0098] Machine (e.g., computer system) **900** may include a hardware processor **902** (e.g., a central processing unit (CPU), a graphics processing unit (GPU), a hardware processor core, or any combination thereof), a main memory **904** and a static memory **906**, at least some of which may communicate with others via an interlink (e.g., bus) **908**. The machine **900** may further include a display unit **910**, an alphanumeric input device **912** (e.g., a keyboard), and a user interface (UI) navigation device **914** (e.g., a mouse). In an example, the display unit **910**, input device **912** and UI navigation device **914** may be a touch screen display. The machine **900** may additionally include a storage device (e.g., drive unit) **916**, a signal generation device **918** (e.g., a speaker), a network interface device **920**, and one or more sensors **921**, such as a global positioning system (GPS) sensor, compass, accelerometer, or other sensor. The machine **900** may include an output controller **928**, such as a serial (e.g., universal serial bus (USB), parallel, or other wired or wireless (e.g., infrared (IR)) connection to communicate or control one or more peripheral devices (e.g., a printer, card reader, etc.).

[0099] The storage device **916** may include at least one machine readable medium **922** on which is stored one or more sets of data structures or instructions **924** (e.g., software) embodying or utilized by any one or more of the techniques or functions described herein. The instructions **924** may also reside, at least partially, additional machine readable memories such as main memory **904**, static memory **906**, or within the hardware processor **902** during execution thereof by the machine **900**. In an example, one or any combination of the hardware processor **902**, the main memory **904**, the static memory **906**, or the storage device **916** may constitute machine readable media.

[0100] While the machine readable medium **922** is illustrated as a single medium, the term "machine readable medium" may include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that configured to store the one or more instructions **924**.

[0101] The term "machine readable medium" may include any medium that is capable of storing, encoding, or carrying instructions for execution by the machine **900** and that cause the machine **900** to perform any one or more of the techniques of the present disclosure, or that is capable of storing, encoding or carrying data structures used by or associated with such instructions. Non-limiting machine readable medium examples may include solid-state memories, and optical and magnetic media. Specific examples of machine readable media may include: non-volatile memory, such as semiconductor memory devices (e.g., Electrically Programmable Read-Only Memory (EPROM), Electrically Erasable Programmable Read-Only Memory (EEPROM)) and flash

memory devices; magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and compact disk-read only memory (CD-ROM) and digital video disk-read only memory (DVD-ROM) disks.

[0102] The instructions **924** may further be transmitted or received over a communications network **926** using a transmission medium via the network interface device **920** utilizing any one of a number of transfer protocols (e.g., frame relay, internet protocol (IP), transmission control protocol (TCP), user datagram protocol (UDP), hypertext transfer protocol (HTTP), etc.). Example communication networks may include a local area network (LAN), a wide area network (WAN), a packet data network (e.g., the Internet), mobile telephone networks ((e.g., channel access methods including Code Division Multiple Access (CDMA), Time-division multiple access (TDMA), Frequency-division multiple access (FDMA), and Orthogonal Frequency Division Multiple Access (OFDMA) and cellular networks such as Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), CDMA 2000 1x* standards and Long Term Evolution (LTE)), Plain Old Telephone (POTS) networks, and wireless data networks (e.g., Institute of Electrical and Electronics Engineers (IEEE) 802 family of standards including IEEE 802.11 standards (WiFi), IEEE 802.16 standards (WiMax®) and others), peer-to-peer (P2P) networks, or other protocols now known or later developed.

[0103] For example, the network interface device **920** may include one or more physical jacks (e.g., Ethernet, coaxial, or phone jacks) or one or more antennas to connect to the communications network **926**. In an example, the network interface device **920** may include a plurality of antennas to wirelessly communicate using at least one of single-input multiple-output (SIMO), multiple-input multiple-output (MIMO), or multiple-input single-output (MISO) techniques. The term "transmission medium" shall be taken to include any intangible medium that is capable of storing, encoding or carrying instructions for execution by the machine **900**, and includes digital or analog communications signals or other intangible medium to facilitate communication of such software.

[0104] The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments that may be practiced. These embodiments are also referred to herein as "examples." Such examples may include elements in addition to those shown or described. However, also contemplated are examples that include the elements shown or described. Moreover, also contemplate are examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

[0105] Publications, patents, and patent documents referred to in this document are incorporated by reference herein in their entirety, as though individually incorporated by reference. In the event of inconsistent usages between this document and those documents so incorporated by reference, the usage in the incorporated reference(s) are supplementary to that of this document; for irreconcilable inconsistencies, the usage in this document controls.

[0106] In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of "at least one" or "one or more." In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to suggest a numerical order for their objects.

[0107] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with others. Other embodiments may be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is to allow the reader to quickly ascertain the nature of the technical disclosure, for example, to comply with 37 C.F.R. §1.72(b) in the United States of America. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. However, the claims may not set forth features disclosed herein because embodiments may include a subset of said features. Further, embodiments may include fewer features than those disclosed in a particular example. Thus, the following claims are hereby incorporated into the Detailed Description, with a claim standing on its own as a separate embodiment. The scope of the embodiments disclosed herein is to be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. A network, comprising:

N nodes in the network, each of the N nodes comprising T transceivers;

T transceiver node groups, each of the T transceiver node groups comprising a first number of groups of nodes ($N^{1-1/T}$, $N/\log_2 N$), wherein the first number of groups of nodes for a first of the T transceiver node groups having the N nodes assigned consecutively with a second number of nodes per each of the groups of nodes being a function of N ($N^{1/T}$, $\log_2 N$), wherein the first number of group of nodes for a remaining number of the transceiver node groups comprises N nodes with transceivers arranged to provide access to any node within a predetermined number of hops ($N^{1/T}$, $\log_2 N$);

wherein an arrangement of the second number of nodes per each of the groups of nodes in the T transceiver node groups provides an optimized throughput per node.

2. The network of claim **1**, wherein the first number of group of nodes is $N^{1-1/T}$.

3. The network of claim **1**, wherein the first number of group of nodes is $N/\log_2 N$.

4. The network of claim **1**, wherein the function of N for the second number of nodes per each of the groups of nodes is $N^{1/T}$.

5. The network of claim **1**, wherein the function of N for the second number of nodes per each of the groups of nodes is $\log_2 N$.

6. The network of claim **1**, wherein the optimized throughput per node is given by

$$\theta\left(\frac{1}{N^{1/T}}\right).$$

7. The network of claim **1**, wherein the optimized throughput per node is given by

$$\Theta\left(\frac{1}{(\log_2 N)^2}\right).$$

8. The network of claim **1**, wherein T is equal to 2, and the first transceiver node groups is grouped into $N^{1-1/T}$ channels, each channel comprising containing $N^{1/T}$ nodes, consecutively numbered nodes being assigned to each channel, and wherein a second transceiver of all nodes is grouped into $N^{1-1/T}$ channels, each channel comprising containing $N^{1/T}$ nodes, the $N^{1-1/T}$ channels for the first transceiver node group including a first transceiver of the N nodes of each channel and the $N^{1-1/T}$ channels for the second transceiver node group including a second transceiver of the N nodes of each channel.

9. The network of claim **8**, wherein the first and second transceivers for the N nodes are arranged to use orthogonal frequencies.

10. The network of claim **1**, wherein the arrangement of the second number of nodes per each of the groups of nodes in the T transceiver node groups comprises a network model based on a channel model, a traffic model and a channel assignment model, and a scaling behavior of the throughput is characterized as a function of the N nodes.

11. The network of claim **10**, wherein the channel model include a wireless network of N nodes, where all nodes are within a transmission range of each other.

12. The network of claim **10**, wherein the traffic model comprises an N source-destination pair random unicast model, wherein every node is a source of one unicast session destined to another node of the N nodes chosen uniformly at random.

13. The network of claim **10**, wherein the channel assignment model comprises a static channel assignment where a particular assignment, once assigned, is used for a predetermined period of time.

14. The network of claim **1**, wherein a scheduling strategy is used for setting transmission times for each of the transceivers in the T transceiver node groups, the scheduling strategy providing a same fraction of time to transmit on a channel associated with the group.

15. The network of claim **1**, wherein a routing strategy is used for controlling transmission form a source node, s, to a destination node, d, wherein the routing strategy comprises the source node, s, transmitting directly to the destination node, d, in one hop on a channel associated with the source node when the destination node is in the group of the source node.

16. The network of claim **1**, wherein a routing strategy is used for controlling transmission form a source node, s, to a destination node, d, wherein the routing strategy comprises a source node, s, transmitting directly to a related node, r, disposed in a group of the source node and sharing a group of the destination node.

17. The network of claim **1**, wherein a node generates packets at a rate

$$\frac{\lambda}{N-1}$$

packets per second, and wherein a total traffic load on a second transceiver of a node is given by

$$\frac{\lambda M(M-1)}{N-1}.$$

18. A method for providing channel assignment processes for high density multi-channel multi-radio (MC-MR) networks wireless networks, comprising:

providing N nodes in a network, each of the N nodes comprising T transceivers;

providing T transceiver node groups, each of the T transceiver node groups comprising a first number of groups of nodes;

assigning the N nodes consecutively for the first number of groups of nodes for a first of the T transceiver node groups having the N nodes;

arranging a second number of nodes per each of the groups of nodes as a function of N; providing the first number of group of nodes for a remaining number of a transceiver node groups of N nodes with transceivers arranged to provide access to any node within a predetermined number of hops; and

using an arrangement of the second number of nodes per each of the groups of nodes in the T transceiver node groups to provide an optimized throughput per node.

19. The method of claim **18**, wherein the providing the first number of group of nodes comprises providing $N^{1-1/T}$ group of nodes.

20. The method of claim **18**, wherein the providing the first number of group of nodes comprises providing $N/\log_2 N$ group of nodes.

21. The method of claim **18**, wherein the arranging a second number of nodes per each of the groups of nodes as a function of N comprises arranging a second number of nodes per each of the groups of nodes as a function of $N^{1/T}$.

22. The method of claim **18**, wherein the arranging a second number of nodes per each of the groups of nodes as a function of N comprises arranging a second number of nodes per each of the groups of nodes as a function of $\log_2 N$.

23. The method of claim **18**, wherein the using an arrangement of the second number of nodes per each of the groups of nodes in the T transceiver node groups to provide an optimized throughput per node of

$$\theta\left(\frac{1}{N^{1/T}}\right).$$

24. The method of claim **18**, wherein the using an arrangement of the second number of nodes per each of the groups of nodes in the T transceiver node groups to provide an optimized throughput per node of

$$\Theta\left(\frac{1}{(\log_2 N)^2}\right).$$

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