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Transmitter Macrodiversity in Multihopping - SFN Based Algorithm for Improved Node Reachability and Robust Routing

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***Abstract*—**A novel idea presented in this paper is to combine multihop routing with single-frequency networks (SFNs) for a broadcasting scenario. An SFN is a set of multiple nodes that transmit the same data simultaneously, resulting in transmitter macrodiversity. Two of the most important performance factors of multihop networks, node reachability and routing robustness, are analyzed. Simulation results show that our proposed SFN-D routing algorithm improves the node reachability by 37 percentage points as compared to non-SFN multihop routing. It shows a diversity gain of 3.7 dB, meaning that 3.7 dB lower transmission powers are required for the same reachability. Even better results are possible for larger networks. If an important node becomes inactive, this algorithm can find new routes that a non-SFN scheme would not be able to find. Thus, two of the major problems in multihopping are addressed; achieving robust routing as well as improving node reachability or reducing transmission power.

***Keywords*—**OFDM, single-frequency networks (SFN), DSFN, MANET; multihop routing, transmitter macrodiversity, broadcasting.

I. Introduction

AN important trend in emerging wireless technologies is low-cost infrastructure and dynamic radio resource management schemes that reduce expensive man-power for manual network planning. An example of this trend is wireless multi-hop networks, which are wireless nodes that are capable of dynamically forming a temporary network without any established infrastructure [1]. Whenever needed, intermediate nodes forward data from a source node to the destination nodes. The network is dynamically self-structured and self-constructed where the nodes in the network can establish and maintain mesh connectivity automatically among them [2]. Possible application examples are mobile ad-hoc computer networking (MANET), sensor-actuator networks, visual sensor networks, ultra-wideband (UWB) wireless-USB routers, and wireless digital radio and TV distribution.

A broadcasting service is desirable since it would feature efficient transmission of data from a source (typically an access point) to a vast amount of nodes – as opposed to sending the same data to one node at a time using unicasting. Broadcasting application examples are actuator control data, software updates and real-time multimedia distribution.

Multihop network nodes are often battery driven devices, requiring low energy consumption and low transmission power, resulting in short *transmission range* or coverage area of each node [3]. *Node reachability* or *coverage probability* is the probability that a destination node is within the transmission range of either the source node or a forwarding node, i.e. that a multihop routing path can be formed from the source to the destination node. A non-reachable node is said to be in a state of *outage*. A reachability of *p* corresponds to an outage probability of 1-*p*.

Transmitter macrodiversity implies that several nodes transmit the same signal simultaneously to a destination node or a forwarding node. In cellular communication, this may be used for so called soft-handover. Using radio/TV broadcasting terminology, the group of transmitters sending the same signal are said to form a *single-frequency network* (SFN) [4]. This can improve the received signal strength and coverage area as compared to non-SFN schemes [5]. OFDM modulation [6] can efficiently eliminate inter-symbol interference (ISI) and combat fading caused by this artificial multi-path propagation. Changing the SFN formation adaptively is called Dynamic Single Frequency Networks (DSFN). DSFN may improve the system spectral efficiency in bit/s/Hz/site by a factor of more than 4 in a simple cellular network [7].

Robust routing means that a new path can be found when one or more nodes die, e.g. due to lack of power supply. A *key node* is very important since a whole network section depends on that it can forward data. The key node typically consumes much more energy than other nodes since it is forwarding data so often, meaning that it will die earlier than other nodes. As a result network sectioning or network collapse may occur, which is one of the major problems of multihop routing.

II. Algorithms

Two ideas; multihop routing and transmitter macrodiversity for a broadcasting service will be combined in our proposed SFN-D algorithm in order to reduce outage probability and increase the routing robustness.

A. A Simple Example

Suppose there are 6 nodes in a network. See Fig. 1. The source N1 (typically the access point AP) will try to broadcast to as many of the other nodes as possible. Node N2 is within

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the transmission range (or node coverage area) of N1. Multihop routing results in that also node N2, N3 and N4 can be reached, since N2 and N3 are forwarding data. Node N5 and N6 can not be reached, but are in a state of outage even after multihopping. The coverage probability including node N1 is 4/6=66.7%, corresponding to an outage probability of 33.3%.

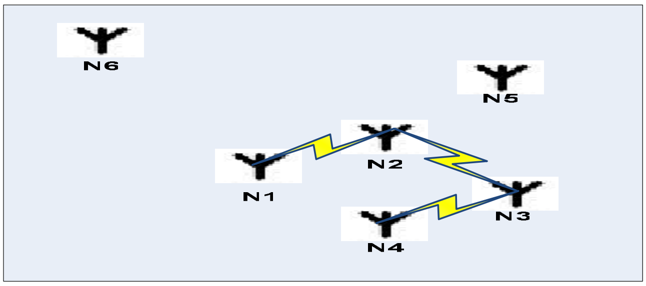

Fig. 1 Four nodes are connected with non-SFN multihopping

Fig. 2 shows that an SFN formation algorithm is applied. If node TX1, TX2, TX3 and TX4 form an SFN and send the same data simultaneously, the *network coverage area* (the white area) is extended, and RX5 can be reached within the coverage area. But still RX6 are out of coverage and is in a state of outage. The coverage probability including node N1 is 5/6 = 83.3%. The improvement is 16.7 percentage points.

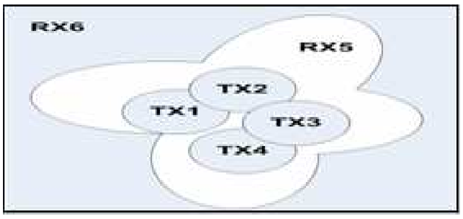

Fig. 2 SFN formation with 4 transmitters makes it possible to connect a fifth node

A simple SFN formation algorithm that assigns a minimum number of transmitters to an SFN follows [7]:

1. Start with an empty set of transmitters assigned to the SFN.
2. Include the transmitter that is nearest to the receiver node in the SFN transmitter set
3. If the signal-to-noise ratio is sufficient, stop. Success.
4. If all the already connected nodes are added, stop. The receiver node is in a state of outage.
5. Add the nearest transmitter that is not already included.
6. Go to step 3.

B. *Non-SFN Multihopping Algorithm*

As a reference case, a non-SFN multihopping algorithm is evaluated. This algorithm is based on two steps where connected nodes of the access point are found out at the first step and multihopping is employed to increase the coverage area at last step. A JSP (Jackson structured programming) chart of the non-SFN multihopping algorithm follows.

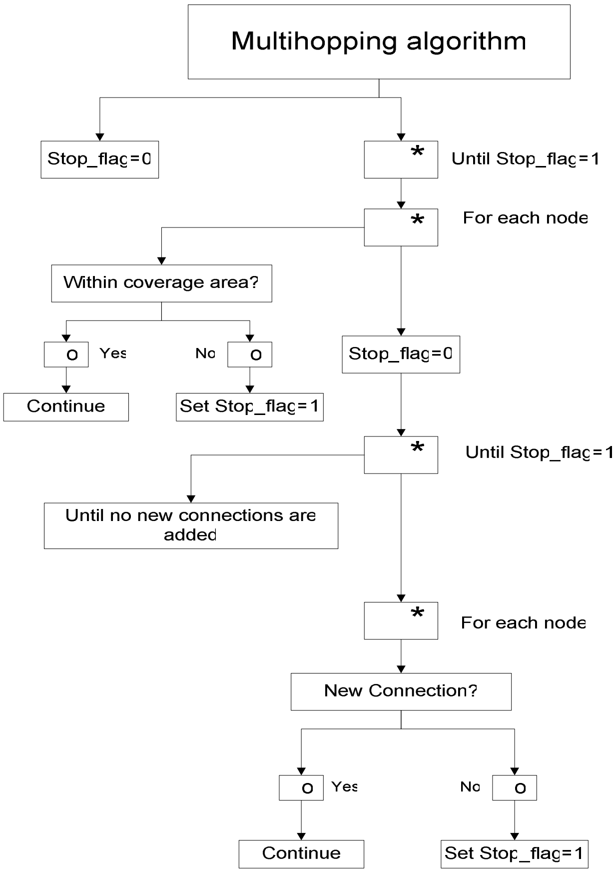

Fig. 3 JSP chart of the non-SFN multihopping algorithm. Asterisk (*) indicate iteration. Circle (o) indicates selection

C. *SFN-D Algorithm*

The primary objective of the SFN-D algorithm is to form minimum size SFNs whenever increased network coverage can be achieved. It should however use non-SFN multihopping whenever possible, since sending from several transmitters would cause higher energy consumption in the network. See Fig. 4. N1 and N2 are connected nodes and the source node (AP) is able to reach N1 and N2 since they are within the coverage area of AP. N1 is able to reach N3 and N2 is able to reach N4 through multihopping. N3 is able to reach N5 and N5 is able to reach N6 through multihopping. N5 and N6 will form SFN to reach N7. And at last N7 can reach to N8 through multihopping.

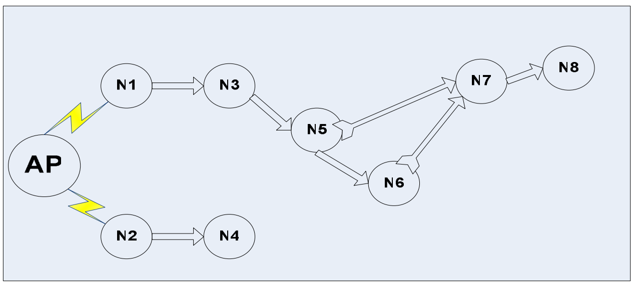

Fig. 4 Simple illustration of the SFN-D algorithm

This algorithm is divided into several steps where connected nodes of the access point are found out at the first step. Then multihopping is employed to increase the coverage area and then SFN is deployed to reduce the outage probability. This algorithm has given more priority to multihopping in comparison with SFN formation. Because multihopping will be employed at first and SFN formation will not be employed until and unless it is required to reach distant nodes. SFN will be employed when multihopping fails to reach any node and then again multihopping will be employed to continue. Overlapping of steps will continue until Max SFN size fail to detect any node. Pseudo code of SFN-D algorithm is as follows:

```
1. Try direct connection of nodes with access point (one hop).
2. Try multihopping, over and over again.
Until no new connections are added.
3. Try SFN size 2.
If new connection: Go to step2.
4. Try SFN size 3.
If new connection: Go to step2.
Same as previous.
Etc.
Stop when Max SFN size is reached.
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III. Simulation Model

Fading, routing initiation phase and protocol timing are not considered in our proposed SFN-D algorithm. The following exponential wave propagation model is assumed, where the signal strength $P_{i,j}$ receiver in node j and transmitted from node i is:

$$P_{i,j} = \frac{G_{i,j} P_i}{d_{i,j}^{\ \alpha}} \quad (1)$$

Here P_i is the transmission power of node I; $d_{i,j}$ is the distance from node i to j; α is an exponent; and $G_{i,j}$ =G is a path gain factor that depends on carrier frequency, antenna heights, fading, etc, but is here assumed to be constant.

The received signal strength is different for different OFDM sub-carriers, but since all inter-symbol interference (self-interference) is assumed to be eliminated, the average received signal strength in node j is assumed to be the sum of the signal strengths from all transmitters belonging to the SFN. This means that the signal-to-noise ratio (SNR) at receiver j can be modeled according to the following:

$$SNR_j = \frac{\sum_{i \in SFN} P_{i,j}}{N} \quad (2)$$

Where N is the noise and interference power. The values of these parameters can be calculated from the following table.

TABLE I
SIMULATION PARAMETERS

Factors	Values
Topology size	100·100meter^2
Node density	0.01/meter^2
Propagation exponent	4
Range of each node	10 meters
Range of access point	20 meters
Transmission power	-10.3 dBm
Receiver sensitivity	-80.5 dBm
Required SNR	4 dB
Size of a packet	1024 bit
Transmission or reception energy/packet	25nJ

IV. Simulation Results

Both the algorithms were simulated and compared regarding reachability and routing robustness. OFDM based IEEE 802.15.3a ultra-wide band (UWB) equipment [8] with characteristics given in table 1 is assumed.

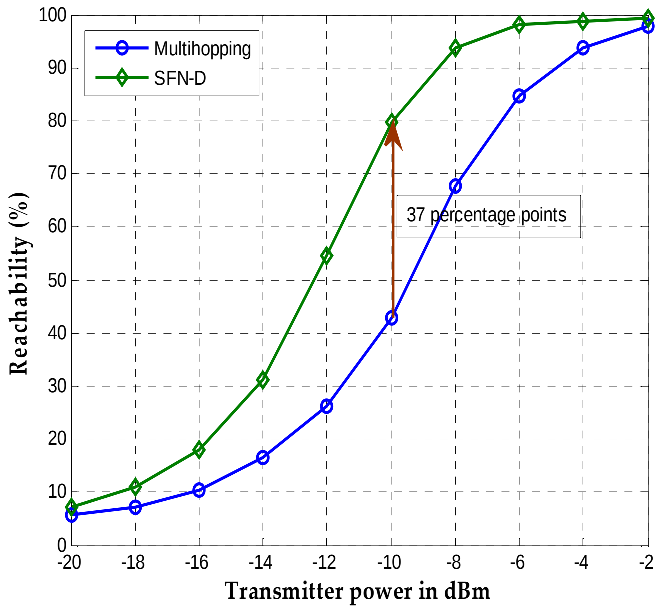

Fig. 5 Comparison of non-SFN and SFN-D algorithms

Fig. 5 shows that SFN-D reaches 98% reachability at -6.0 dBm Tx power whereas non-SFN multihopping needs -2.47 dBm to for the same reachability, i.e. a diversity gain of 3.5 dB. At a certain Tx power (-10dBm), SFN-D gives 79% as compared to 42% of the non-SFN algorithm, meaning a reachability gain of 37 percentage points. Fig. 6 shows that SFN-D achieves 46 percentage points more reachability than non-SFN for the network size 210·210 m^2 and can maintain it also for larger network sizes.

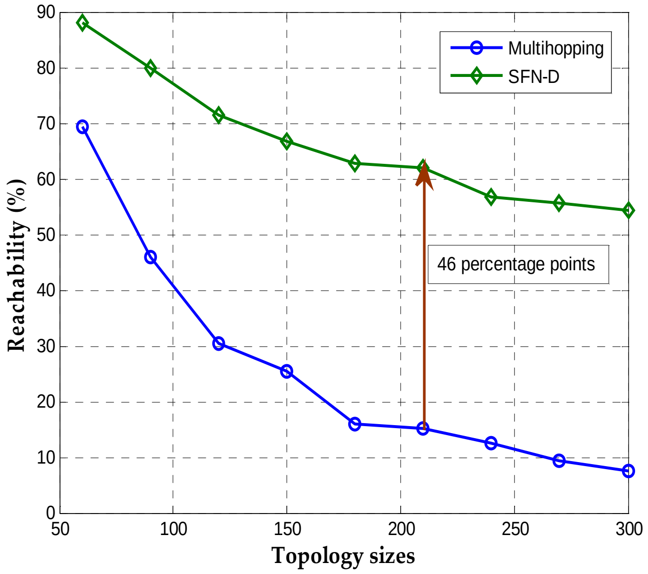

Fig. 6 Comparison of the non-SFN and SFN-D algorithms

A random example is shown in Fig. 7 and 8. The access point is sited in the middle where red circle indicate its range. All other nodes are at random positions. Blue lines represent the direct connection between access point and the nodes, red lines represent the multihopping and green line represents SFN formation.

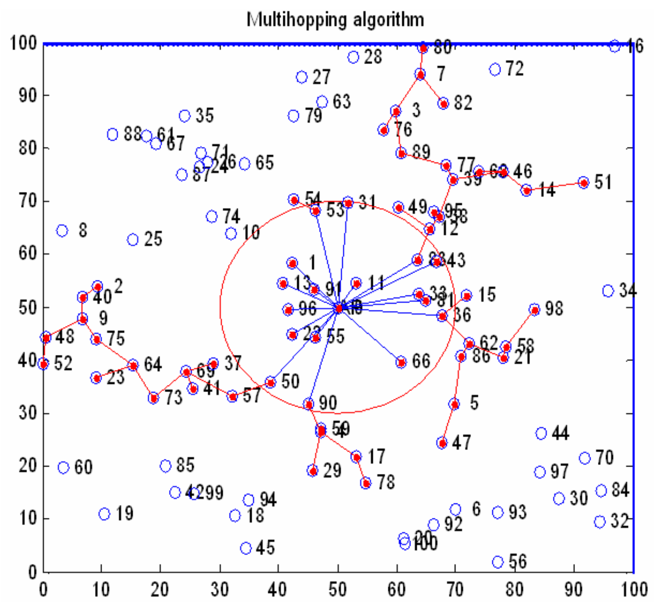

Fig. 7 Example of non-SFN multihop routing

In this example, the non-SFN multihopping algorithm has a reachability of 60% of the nodes, whereas SFN-D gives a reachability of 78%. So, SFN-D increases the reachability by 18 percentage points.

The routing instability of the non-SFN algorithm is illustrated in Fig. 9. Node 64 and 89 can be considered as important nodes since a large number of nodes depend upon them. If node 64 and 89 run out of energy and die, the routing cannot find alternative paths in this example, resulting in that another 12 nodes lose their connection with the access point.

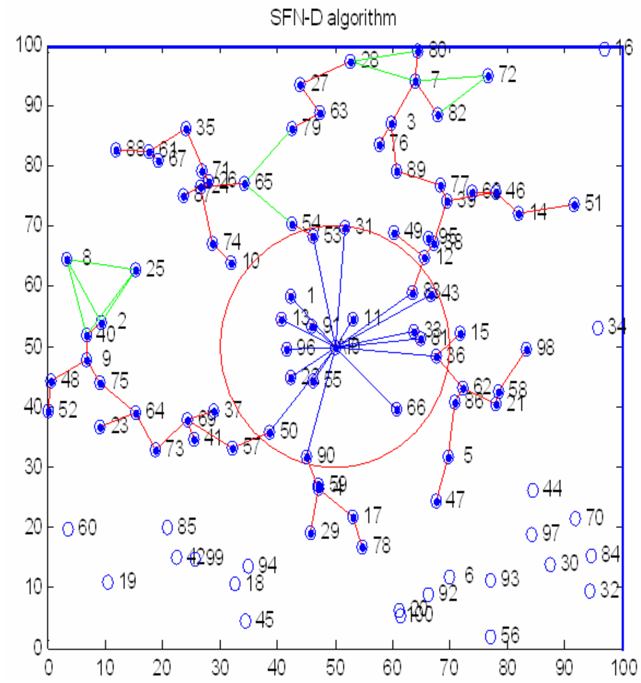

Fig. 8 Example of SFN-D multihop routing

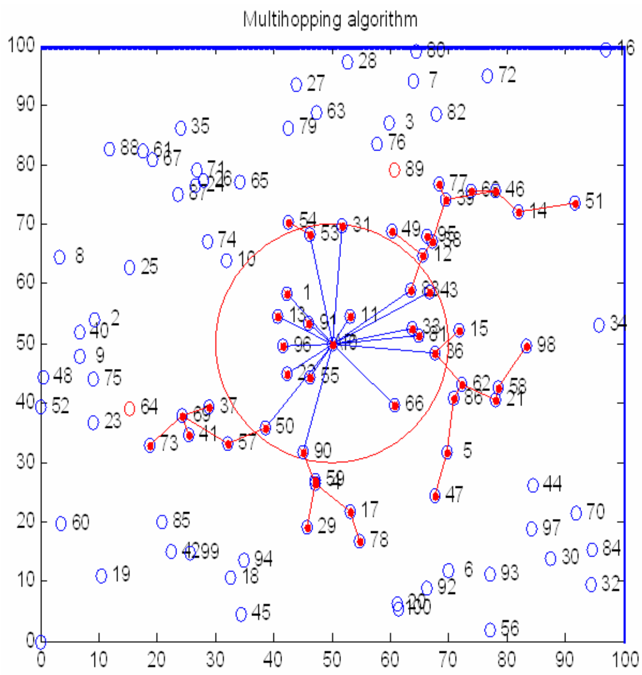

Fig. 9 Instability of non-SFN routing, if node 64 and 89 dies.

In the SFN-D case, SFNs are formed and gives alternative paths when node 64 and node 89 die. See Fig. 10. Conseqently, the connectivity remains stable and robust.

In the Fig. 11 example, another two important nodes, node 62 and 12, die. In this case, SFNs are not formed, but alternative paths are still found.

These two severe cases indicate that SFN-D improves the robustness towards dying nodes.

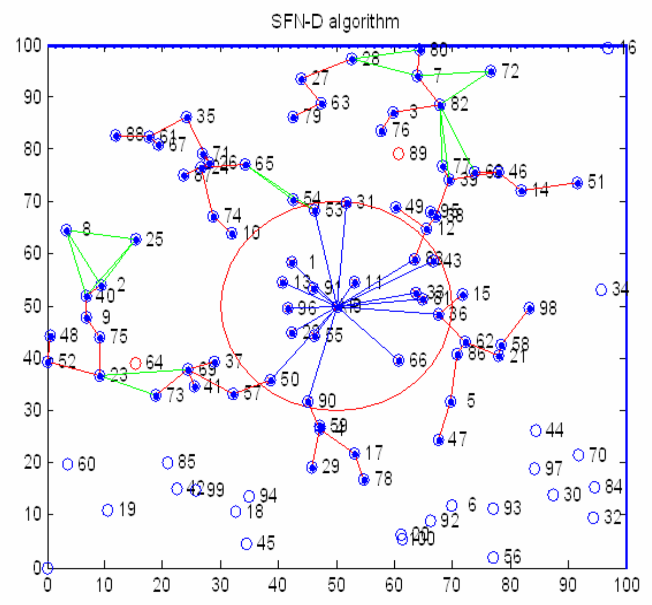

Fig. 10 Routing stability of SFN-D, if node 64 and 89 dies.

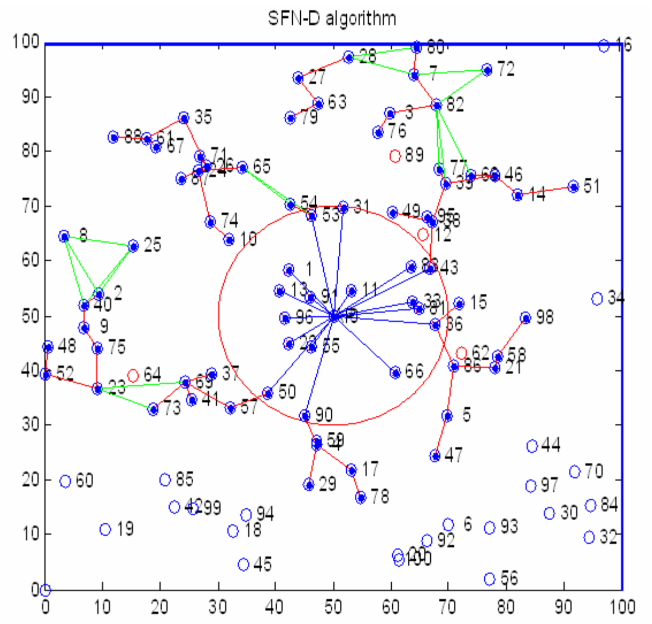

Fig. 11 Routing stability if another two nodes die

V. CONCLUSION

The results of this study show that the node reachability was improved by up to 37 percentage points as compared to non-SFN multihop routing. SFN-D only requires transmission power of -8.7 dBm where non-SFN multihopping requires -5 dBm to maintain a node reachability of 90%. This means that the algorithm provides a diversity gain of up to 3.7 dB. The results indicate that the algorithm is capable of producing even better diversity and reachability gain for larger networks than the simulated 100 nodes.

Most importantly this algorithm addressed one of the key problems of multihopping since it is capable of keeping the network robust even if one or more important nodes die. If a key node becomes inactive, this algorithm can find new routes that a non-SFN scheme would not be able to find by forming an SFN. Consequently, network partitioning is avoided.

A return path may not always be available from a node that only can be reached from an SFN. During the routing initiation phase, when SFNs are formed, a two-way communication path is required for exchanging signal strength measurements. A node that can not be reached during the initiation phase, before SFNs are formed, can not be assigned to an SFN. A conceivable solution to these problems is to increase the transmission power and/or use more robust but less efficient transmission such as a spreading code during the routing initiation and for the return path.

Future work include studying energy consumption, protocol design and timing, routing initiation and distributed algorithm implementations. The concept can be applied to unicasting and multicasting, and combining or comparing SFNs with other dynamic radio resource management techniques, for example ARQ, link adaptation and power control.

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