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Dynamic Single Frequency Networks in Wireless Multihop Networks

Energy aware routing algorithms with performance analysis

Magnus Eriksson and *Arif Mahmud*
E-mail magnus.eriksson@miun.se and arif_mahmud_ankur@yahoo.com
Dept. of Information Technology and Media, Mid Sweden University, Sundsvall, Sweden

***Abstract*— A new approach to improving the energy consumption and node reachability of multihop networks is to dynamically combine multihop routing with single-frequency networks (transmitter macrodiversity), i.e. several nodes sending the same signal simultaneously over the same frequency channel. Four routing algorithms are suggested and evaluated for a broadcasting scenario. Simulation results show that the best algorithm reduces the energy consumption by up to 42% in comparison to non-SFN multihop routing for the same node reachability. SFN-based multihop routing improves the reachability by up to 37 percentage points as compared to non-SFN routing. A 3.8 dB diversity gain is observed that allows a 54% higher data rate for the same bit error probability. By restricting the SFN sizes to a maximum number of nodes, the energy efficiency may be improved while the reachability is deteriorated.**

Keywords: Multihop routing, sensor networks, simulcasting, SFN, DSFN, UWB, MANET, macrodiversity.

I. Introduction

Multihop routing is expected to be a key component in future wireless communication techniques such as mobile ad-hoc computer networking (MANET), WLAN mesh networks, wireless sensor-actuator networks (WSAN) and ultra-wideband (UWB) wireless-USB extension, and may also be useful in wireless digital radio and TV distribution.

Low energy consumption, high node reachability (coverage probability) and low emitted transmission power are major concerns in mobile computing and wireless sensor-actuator networks.

In this paper, these issues are addressed by *transmitter macro-diversity* or *simulcasting*, meaning that several network nodes send the same signal. If this is conducted over the same frequency channel, the transmitting nodes are said to form a *single-frequency network* (SFN). Multihop routing schemes that form SFNs are suggested and analyzed.

Fig.1 illustrates how SFNs improve the signal-to-noise ratio and extend the coverage area. An SFN size of 3 nodes apparently provides better node reachability than 2 nodes, but also causes higher energy consumption in the system and a shorter battery time since more nodes are employed in data forwarding.

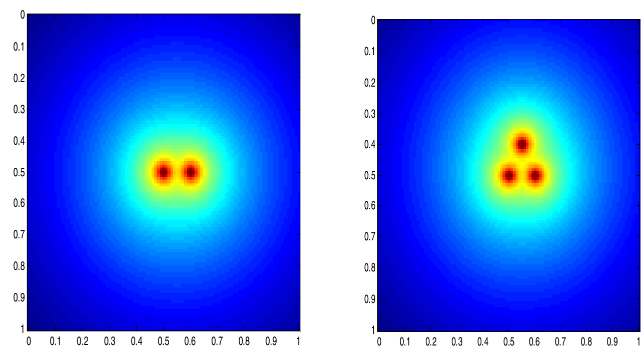

Fig. 1: Signal-to-noise ratio of single-frequency networks of size 2 nodes (left) or 3 nodes (right).

The fading and inter-symbol interference caused by this artificial multi-path propagation may be combated by spread spectrum with rake receivers, or by OFDM modulation or other frequency domain equalization (FDE) schemes.

The SFN term originates from the digital radio and TV broadcasting world, where OFDM modulation makes it possible for a network of transmitters to simulcast the same radio/TV program over the same channel frequency [1]. The main objective is a increase the system spectral efficiency (number of radio programs per MHz and site).

The concept of Dynamic Single Frequency Networks (DSFN) was suggested in 1999 [2], and implies that SFNs are formed dynamically in OFDM-based cellular networks with a view to improving the signal quality for exposed mobiles. A scheduling algorithm adapts the SFN formations to the traffic and channel conditions in order to optimize the system aggregated throughput. An improvement of up to 370% of the fairly shared system spectral efficiency in bit/s/Hz/site was observed in a simple cellular system.[3]

Similar concepts were studied for cellular communication in e.g. [4] and [5], where the latter is about *soft handover* in OFDM based systems. In [6], up to 2.63 dB diversity gain was achieved together with an improved capacity of 20%, after applying OFDM-SFN to a typical cellular system without making significant changes to the running infrastructure.

The recent 3GPP long-term evolution (LTE) cellular standard, includes the *multicast-broadcast single frequency*

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TABLE I. MODEL PARAMETERS

Factors	Values
Range of each node*	10 meters
Range of source node (access point, AP)	20 meters
Radiated node transmission power, P_{Tx}* (Higher for the AP)	-10.3 dBm $= 9.3 \cdot 10^{-5}$ W
Receiver sensitivity	-80.5 dBm
Required SNR	4 dB
Topology size A*	$100 \cdot 100$ meter^2
Number of nodes N*	100
Node density N/A	0.01/meter^2
Length of a packet L	1024 bit
Energy consumption E_{Rx} for reception	20 nJ/bit
Energy consumption E_{Tx} for transmission if the above transmission power is used*	30 nJ/bit

*) Varied in some simulations

network (MBSFN) technology for efficient transmission to several users in adjacent cells. In the upcoming 4G LTE-Advanced system, *coordinated multipoint transmission/reception* (CoMP) is a suggested technology for soft handover for unicast communication, with the aim to improve the signal quality in exposed positions in-between several base stations. [7]

SFNs is a space diversity technique that does not require any extra signal processing or coding, which makes it interesting in battery driven equipment such as wireless sensor-actuator network nodes.

The application of transmitter macrodiversity to multi-hop networks and relay channels is suggested in [8], where it is combined with automatic repeat request (ARQ) and analyzed for a unicast service. Here erroneous packets result in that multiple intermediate relay nodes concurrently retransmit the packet to the destination node. A possible reduction of the emitted transmission power is thus observed. It was concluded that "whenever the opportunity to exploit macrodiversity presents itself, it should be taken." However, this conclusion was made without energy consumption in mind.

Our previously published results show that if important forwarding nodes in a multihop network die due to e.g. limited battery capacity, an SFN based routing scheme may find more alternative paths than a non-SFN scheme is able to, resulting in more robust and stable routing.[9]

In this paper, a broadcasting scenario is considered. An efficient broadcasting service is desirable since this would provide high capacity for data transfer to a large number of destination nodes. Application examples that benefit from efficient broadcasting include real-time multimedia distribution, visual sensor networks, software updates, actuator control data, routing table updates and system parameter updates.

An energy consumption model that depends on the transmission power is suggested and the energy consumption are calculated for simple non-SFN and SFN routing examples (in section II). Three multihop broadcast routing schemes involving SFN:s are suggested (in section III), compared (in section IV) and analyzed (in section V).

II. SIMULATION MODEL AND PERFORMANCE MEASURES

OFDM based IEEE 802.15.3a ultra-wide band (UWB) equipment [8] with characteristics given in table 1 is considered.

A. *Wave propagation model*

A wave propagation model is assumed, in which the signal strength is exponentially attenuated with the distance. The signal strength from transmitting node i and received at node j is modeled as:

$$P_{i,j} = \frac{P_i F_{i,j} G_{i,j}}{d_{i,j}^{\alpha}}. \tag{1}$$

Here P_i is the transmission power and $d_{i,j}$ represents the distance between transmitter i and receiver j. No fading is considered, i.e. the fading factor $F_{i,j} = 1$. The exponent α is assumed to be 4. A constant antenna gain $G_{i,j}$ is calculated from table 1.

B. *Signal quality model*

The SFN causes a total signal-to-interference and noise ratio (SINR) at receiver j, and is modeled as [3]

$$\Gamma_j = \frac{\sum_{i \in \mathbb{U}_j} P_{i,j} w_{i,j}}{\sum_{i \in \mathbb{I}_j} P_{i,j} + \sum_{i \in \mathbb{U}_j} P_{i,j}\left(1 - w_{i,j}\right) + I_{\mathrm{Ext},j}} \approx \frac{\sum_{i \in \mathbb{U}_j} P_{i,j}}{\sum_{i \in \mathbb{I}_j} P_{i,j} + I_{\mathrm{Ext}}}, \tag{2}$$

where $P_{i,j}$ is the power from transmitter i received in receiver j; $\mathbb{U}_j \subseteq \mathbb{TX}$ is the set of transmitters in the SFN assigned to receiver j (the useful signals); $\mathbb{I}_j = \mathbb{TX} \backslash \mathbb{U}_j$ is the set of transmitters sending other signals (co-channel interferers or packet collisions, not considered in our simulations); $w_{i,j} \in [0,1]$ is a weighting factor which depends on the inter-symbol interference (ISI) and Doppler shift, and $I_{\mathrm{Ext},j}$ is the noise and external interference power. In our simulations, no ISI and Doppler shift are assumed, due to short transmitter distances, sufficient OFDM guard interval and moderate mobility. This leads to the approximation in the last term of (2). The noise and interference level I_{Ext} is assumed to be constant and is calculated from table 1.

C. *Energy consumption model*

The following total energy consumption model for the whole system is suggested:

$$E_{Tot} = \left(N_{Tx} E_{Tx} + N_{Rx} E_{Rx}\right) L, \tag{3}$$

where N_{Tx} is the number of data packet transmissions, and N_{Rx} the number of data packet receptions. The other parameters are defined and given in table 1.

The energy consumption per bit for a node that is transmitting data is assumed to depend on the radiated transmission power P_{Tx} in watts according to:

$$E_{Tx} = \left(E_{Rx} + \frac{P_{\mathrm{Tx}} \left(E_{Tx} - E_{Rx} \right)}{P_{Tx0}} \right), \tag{4}$$

where $P_{\mathrm{Tx0}} = 9.3 \cdot 10^{-5}$ W is a reference level.

The average performance is evaluated for hundreds of random node position topologies.

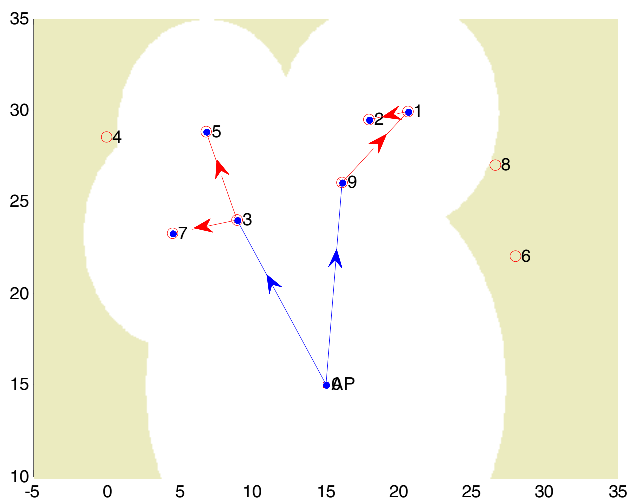

Fig. 2: Simple non-SFN example. The access point (AP) is source node. Lines represent multihop forwarding. The signals from the transmitting nodes can be received within the white area.

D. A simple non-SFN multihop example

Fig. 2 illustrates a non-SFN multihop case. The access point (AP) is a source node that is broadcasting data addressed to the other nine nodes. Nodes 3 and 9 are within the range of the AP, and can be immediately connected (blue lines). These may forward data to nodes 1, 2, 6 and 7 which can be reached by means of multihopping (red lines).

Nodes 4, 6 and 8 cannot be reached unless SFN formations are utilized, but would be in a state of outage. Consequently the node reachability (the coverage probability) would be 6/9, corresponding to an outage probability of 3/9, in the non-SFN case.

In this non-SFN case (Fig. 2), the number of packet transmissions N_{Tx} in the whole system is equal to the number of transmitting nodes, which in this example is 4. The number of packet receptions N_{Rx} in the whole system is in a non-SFN case equal to the number of receiving nodes, which in this example is 6.

E. A simple SFN multihop example

Fig. 3 shows that the reachability may be extended through SFN formation. Nodes 5 and 7 form an SFN of size S_1=2 nodes, which may reach node 4. Nodes 1, 2 and the AP may form an SFN of size S_2=2 nodes, to reach node 6. Node 6 may be considered as an “SFN” of size S_3=1 (meaning non-SFN multihopping) which may forward data to node 8.

The number of packet transmissions N_{Tx} would increase by S_1+S_2+S_3=5 to 9. The retransmitted packet will be ignored by nodes that have already received it, for example nodes 3 and 9, after they have recognized its header. The energy consumption for this is ignored. In this example the number of packet receptions N_{Rx} would increase by 3 to 9.

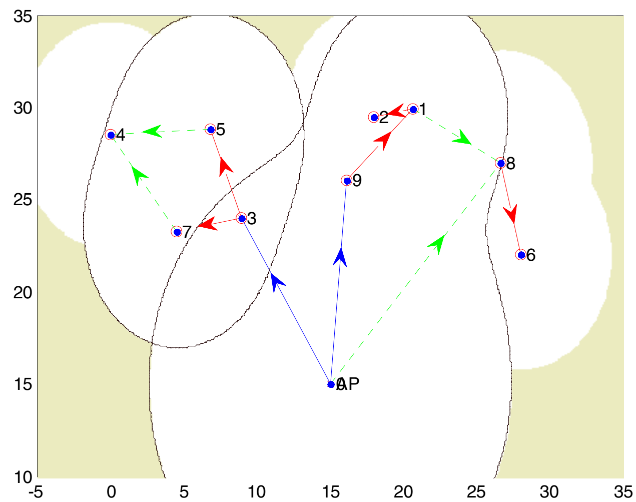

Fig. 3: Simple SFN example. Dotted green lines represent SFN formations, meaning that several nodes send the same signal concurrently. The curves indicate the coverage area of the two SFNs.

III. Routing Algorithms

The objective of the following multihop routing schemes is to provide sub-optimal solutions to the problem of, firstly, maximizing the reachability and, secondly, minimizing the energy consumption. The algorithms can be considered as heuristic optimization algorithms. Simplified algorithm pseudo code is provided, which only returns the set $\mathbb{C}$ of connected (or reachable) nodes. Centralized models of the algorithms are provided here, while in a real implementation, distributed versions of the algorithms would be necessary.

A. Non-SFN algorithm

As a reference case, a non-SFN shortest-path multihop broadcasting algorithm is evaluated. The objective of this algorithm is to broadcast data to as many nodes as possible, while minimizing the number of hops to each node. However, this does not necessarily minimize the energy consumption. In a first step, nodes that are immediately connected to the source node are found out, i.e. within zero hops. As a second step, one-hop multihopping is employed to increase the coverage area, followed by two-hop multihopping, etc. The pseudo-code follows. ℂ denotes the set of connected nodes.

```
ℂ = {the source node}.
For hop counter = 0 to +inf,
    For each node i in ℂ,
        Assume node i is transmitting.
        For each non-connected node j,
            Calculate SNR from i to j,
            If SNR>required SNR,
                ℂ = {ℂ, j}.
        If all connected nodes have been
          checked once without any new node
          being added to the set:
            Break outer loop.
```

B. SFN-A algorithm

The objective of the SFN-A algorithm is to maximize the node reachability but not to minimize the energy utilization. It establishes direct connections and non-SFN multihopping (in a first phase) and SFNs of minimum size 2 nodes (in a second phase). In this rather simple first approach the phases are separate from each other. Non-SFN multihopping is never used after SFNs are formed, even if it would be beneficial from energy consumption point of view. The SFN sizes are restricted by a certain permitted maximum SFN size S_{Max}, in view to limit the energy consumption. Pseudo-code follows. S denotes the SFN size.

```
Call the above non-sfn algorithm.
While true:
    For S = 2, 3… S_Max:
        For each non-connected node j:
            Assume that the S already
              connected nodes that give
              highest signal strength at j
              form an SFN and transmit.
            Calculate the SNR at node j.
            If SNR>required SNR,
                ℂ = {ℂ, j}.
    If no new node were added during
      the last inner loop iteration:
        Break the outer loop.
```

During a routing initation phase, initiated whenever the topology is changed, the nodes are assumed to measure and transfer signal strength estimates $P_{i,j}$ or path losses between each other. Based on these the algorithm can calculate the signal-to-noise ratio of the SFNs that are formed.

C. SFN-B algorithm

The SFN-B algorithm allows overlapping of the SFN and non-SFN phases, meaning that non-SFN multihopping can be employed after SFNs are formed. The objective of the algorithm is firstly to maximize the reachability, secondly to minimize the number of hops, and thirdly to minimize the SFN sizes. Pseudocode:

```
ℂ = {the source node}.
For hop counter = 0 to +inf:
    For each non-connected node j:
        For S = 1 to S_Max:
            Assume that the S already
              connected nodes that give
              highest signal strength at j
              form an SFN and transmit.
            Calculate SNR at j.
            If SNR>required SNR:
                ℂ = {ℂ, j}.
                Break inner loop
                  (i.e. goto next j).
    If no new nodes were added to ℂ:
        Return.
```

D. SFN-D algorithm

The objective of the SFN-D algorithm is firstly to maximize the node reachability, secondly to minimize SFN sizes, and thirdly to minimize the number of hops. This results in the minimum energy consumption. The algorithm gives priority to non-SFN multihopping over SFN formation. The algorithm is divided into several steps where those nodes immediately and non-SFN multihopping (SFN size S=1) is employed as far as it can reach, to increase the coverage area. Then SFN of minimum size is deployed to reduce the outage probability. If an SFN can reach a node, the algorithm starts over again and with employing non-SFN multihopping if possible, etc. This is repeated over and over again until there is an iteration in which no new nodes are detected. Pseudocode:

```
ℂ = {the source node}.
While true:
    For S = 1 to S_Max:
        For each non-connected node j:
            Assume that the S already
              connected nodes that give
              highest signal strength at j
              form an SFN and transmit.
            Calculate SNR at j.
            If SNR>required SNR:
                ℂ = {ℂ, j}.
                Break inner and middle loop
                  (i.e. start over with S=1).
        If S==S_Max
            Return.
```

IV. Results

All four routing algorithms (including the non-SFN algorithm) are evaluated in terms of node reachability and energy consumption. The best SFN algorithm is then compared with the non-SFN algorithm in order to calculate the diversity gain and energy consumption gain. The SFN size is restricted to maximum 5. See fig. 4.

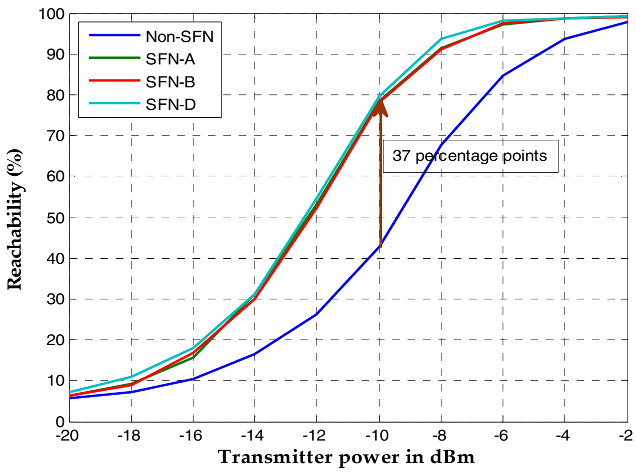

Fig. 4: Node reachability of four algorithms as function of transmission power.

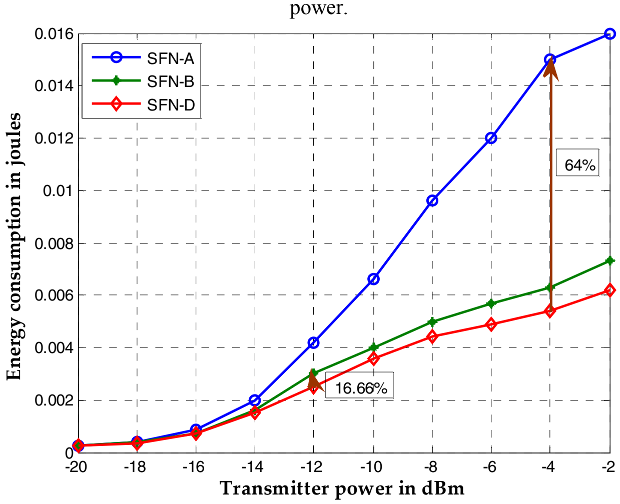

Fig. 5: Energy consumption E_{Tot} in the whole system for sending one data packet, of three SFN algorithms for the same node reachability.

Three algorithms SFN-A, SFN-B and SFN-D reached 80% node reachability in -10 dBm whereas the non-SFN required -6.5 dBm for an equal amount of node reachability. This corresponds to a diversity gain of 3.5 dB. Algorithms SFN-A, SFN-B and SFN-D are more or less equal from a node reachability point of view. Fig. 5 shows a comparison of the three SFN based routing algorithms from an energy consumption viewpoint.

The SFN-D algorithm consumes up to 64% less energy than the SFN-A and 16.66% less energy than the SFN-B to achieve the same amount of node reachability and thus was selected as the best SFN algorithm. Fig. 6 shows the diversity gain achieved by the SFN-D algorithm over the non-SFN algorithm.

To achieve 98% of node reachability, the SFN-D algorithm requires -6.00 dBm while the non-SFN requires -2.5 dBm, corresponding to a diversity gain of 3.5 dB. The maximum diversity gain is achieved by the SFN-D and is 3.8 dB. At the Tx power of -10 dBm, the SFN-D algorithm can achieve 79% of node reachability, whereas

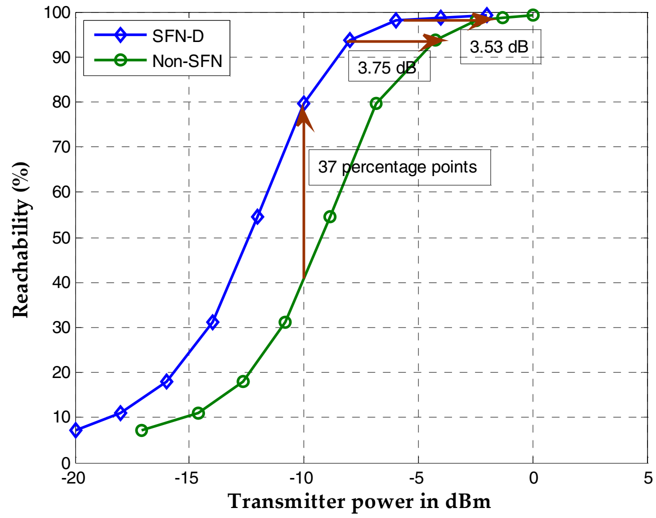

Fig. 6: Comparison of SFN-D and non-SFN algorithms for the same node reachability.

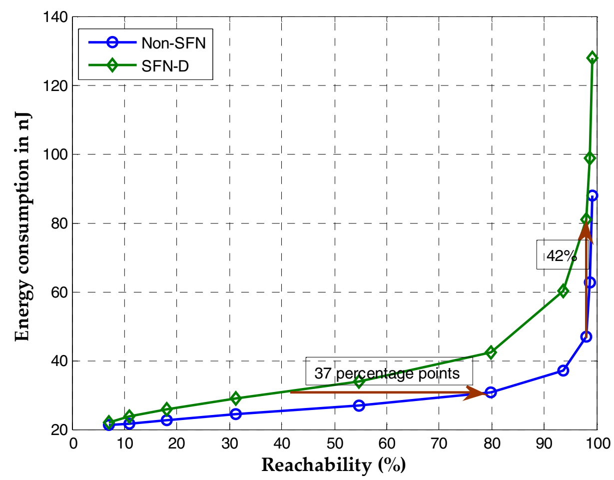

Fig. 7: Energy consumption E_{Tot}/LN in nJ per node and bit for the SFN-D and non-SFN algorithms. Horizontal arrows shows that for a given energy consumption budget, SFN-D can improve the coverage by up to 27.8 percentage points (intermediate data is interpolated).

the non-SFN only achieves 42% of the node reachability. Thus, a node reachability gain of 37 percentage points (or 88%) can be achieved. Fig. 7 demonstrates the energy consumption gain achieved by the SFN-D over the non-SFN algorithm.

It is possible to achieve up to a 41.9% energy consumption gain by using the SFN-D. At a particular energy value (32 nJ) the SFN-D algorithm can achieve 79% of node reachability whereas the non-SFN only provides 42% of node reachability. Thus, a node reachability gain of 37 percentage points can be achieved.

SFN size-2, SFN size-3, SFN size-4, SFN-5 and Max SFN size means that 2 nodes, 3 nodes, 4 nodes, 5 nodes and all the nodes of the network respectively can participate to

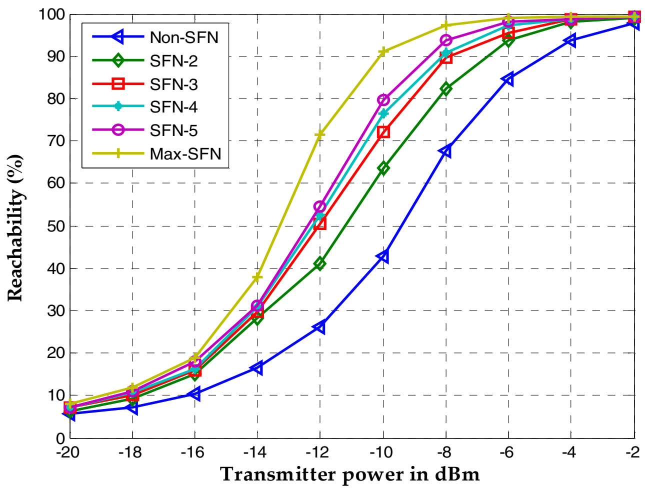

Fig. 8: Comparison of different maximum SFN sizes based on node reachability. The horizontal distance corresponds to the diversity gain.

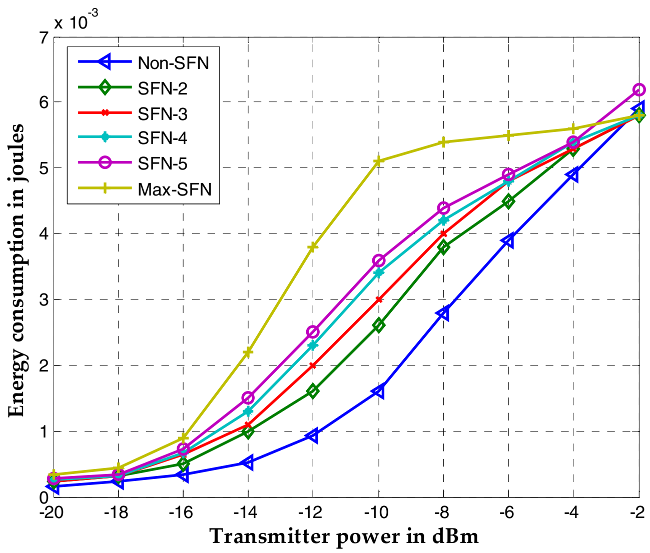

Fig. 9: Energy consumption E_{Tot} of SFN-D as function of transmitter power for different maximum SFN sizes. The diversity gain is not taken into consideration here.

form the SFN. As can be seen in fig. 8, a larger SFN size offers better node reachability.

An unlimited SFN size increases the node reachability when compared to SFN sizes 2, 3, 4 and 5 by up to 30.5, 21.0, 18.9 and 16.8 percentage points respectively. However, to achieve the same node reachability, these schemes require 57.8%, 47.3%, 39.4% and 34.2% more energy than the unlimited SFN size case. See fig. 9.

Note that the SFN-D routing algorithm provides a better performance gain (node reachability, diversity gain and total energy consumption improvement) for a lower density than a higher density of nodes. If the node density increases then both the SFN and non-SFN supported algorithms achieve similar results. However, for the lower node density scenario, more transmission power and energy are spent in order to attain the same node reachability.

A. The two-way communication path problem

A return-channel may not always be available from a node that can only be reached from an SFN. During the routing initiation phase, when SFNs are formed, a two-way communication path is required for transferring signal strength measurements and routing tables. A node that cannot be reached during the initiation phase, before SFNs are formed, cannot be assigned to an SFN.

A conceivable solution to this problem 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 channel. Suppose a 4 dB stronger transmission power, or a 4 dB lower SNR requirement, during the routing initiation phase than during the data transfer phase, and that nodes that cannot be reached during the initiation phase are removed. Then the SFN reachability results of this study would be reduced by 1.5 percentage points for the reference case. If a 5 dB stronger transmission power was assumed, then the reachability results of this study would be reduced by about 0.2 percentage points.

V. Conclusions

Promising results indicate that transmitter macro-diversity or dynamic single-frequency networks are beneficial in several respects for a broadcasting traffic scenario in a multihop network. A *diversity gain* of up to 3.8 dB was observed for the three SFN schemes, meaning that the transmission power can be reduced by 3.8 dB for the same reachability or coverage probability as in a non-SFN system. This diversity gain may be utilized in several alternative ways:

1) A decreased *transmission power* by 3.8 dB allows up to 41.9 % lower *energy consumption* when applying the SFN-D algorithm as compared to the non-SFN case, for the same reachability.

2) The SNR requirement may be increased from 4.0 dB to 7.8 dB by the SFN schemes, while maintaining the same reachability and transmission power. Based on the Shannon–Hartley theorem, this may allow a 54.4% higher *data rate* for an equivalent bit error probability.

3) The *reachability* may be improved by up to 37 percentage points (corresponding to 88%) by the SFN schemes for the same transmission power.

4) A combination of the above.

In alternative 2 and 3, an increased energy consumption is however observed due to increased number of transmitting nodes

These results were achieved for SFN sizes that were restricted to a maximum of five nodes. A larger maximum SFN size allows even higher reachability but is less efficient from energy consumption point of view.

Out of the studies algorithms, SFN-D is most efficient from energy consumption point of view. An important conclusion is that since SFN-D in general offers better energy consumption than SFN-B, low SFN size should be given priority over low number of hops. Thus it can be concluded that from an energy consumption point of view, transmitter macrodiversity should not be employed unnecessarily as this could lead to a waste of energy. An explanation is that although an SFN may reduce the number of hops by e.g. one, the energy consumption would increase if the SFN size is three nodes or more, and sometimes (for large transmission powers) if the size is two.

Even higher diversity gain is expected for a fading model. Improved robustness towards fading and shadowing is expected. The concept is expected to be beneficial even for unicasting and multicasting service scenarios.

Future work includes formulating distributed versions of the routing algorithms, studying protocol design and timing as well as OFDM symbol synchronization mechanisms. To avoid that traffic load from other sources prohibit, or interfere with, SFN formations, timeslot reservation and collision avoidance may be considered. The concept may also be applied to unicast and multicast services, and analyzed for a stochastic channel model including fading. Finally, dynamic SFNs may be combined or compared with other dynamic radio resource management techniques, for example automatic repeat request (ARQ), channel adaptive scheduling, link adaptation and power control.

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