Increasing Connectivity in Wireless Sensor Network using Cooperative Transmission

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Abstract— **Wireless sensor networks are used to perform sensor measurements under a variety of conditions. In settings with sparse distribution of sensor nodes, multi-hop routing is traditionally used to forward information from a source node to a destination node. A problem with this approach is that loss of connectivity of nodes in the path between source and destination may lead to a partitioning of the network.**

We present cooperative transmission to connect previously disconnected parts of a network thus overcoming the separation problem of multi-hop networks. We show that this approach improves connectivity over 50% compared to multi-hop approaches and reduces the number of nodes necessary to provide full coverage of an area up to 30%. The paper presents theory, a comparison of 3 types of cooperative transmission approaches to multi-hop networks and shows the practical feasibility by presenting a prototypical implementation on the *Particle Computer* wireless sensor node platform.

I. INTRODUCTION

Wireless sensor networks gain more and more attention as an instrument for fine-granular measuring of a physical parameter in a given area. A wireless sensor network is a group of wireless sensor nodes of which each contains at least one sensor and a wireless RF communication unit. In the last years, research communities have developed several different wireless sensor network platforms, such as the Motes [1] or Smart-Its [2], [3]. Mentionable business is already being generated through this emerging technology [4]. The sensor nodes are normally distributed over a certain area to give information on relevant physical parameters or events. The measurements taken are then locally interpreted or forwarded to a base-station for further data processing. To forward the data in such a sensor network, the nodes normally perform *multi-hop routing*. Different methods and strategies to optimize this data-flow process have been proposed and compared against each other [5]. In general, a multi-hop network tries to find a route between a source and a destination to forward the information. As a theoretical minimum, at least one route must exist to perform data transport. If two nodes in this route are not able to communicate to each other because they are too far away to send/receive RF-signals the network is segmented. This can happen due to environmental conditions – e.g. higher noise on the channel – , the failure of nodes or simply by wrong set-up of the sensor network.

The installation process of wireless sensor networks can therefore be a very exhausting task. Wireless sensor networks can easily consist of several hundreds of nodes that have to be placed in the area of interest. Instead of manually placing each single node, mass-processes have been proposed to simplify and accelerate this task. On often cited example is to use a plane or helicopter and drop the nodes over a certain area. Then, the sensor nodes randomly distribute in the area and can e.g. perform sensor tasks and multi-hop data forwarding towards a base-station. This random distribution process encounters difficulties when the nodes start to forward their information: it cannot be guaranteed, that a multi-hop connectivity between all nodes and e.g. the access point can be established. The communication range of the nodes will be limited and – depending on the number of nodes in the area (=density) – it is likely that some nodes get isolated as a separated cluster. This can only be avoided by significantly over-provisioning the network by introducing redundancy. Either the radio range or the node density must be significantly increased to ensure a good over-all connectivity among the nodes or towards the access point.

II. SPARSE SETTINGS

The above mentioned process of the random installation of sensor nodes by throwing them out off a plane or helicopter is only one example of how a bad overall connectivity in a wireless sensor network can arise. Not only the installation process but also mobility of the nodes can lead to disadvantageous topologies in a sensor network. Clustering and singulation of nodes can have many reasons. These reasons are often not under the control of the system's supervisor and can therefore not be avoided. The following list shortly discusses a few of the most relevant reasons for connections breaks and clustering in a sensor network:

A. *Random installation process*

If a network is deployed by using a random scatter process such as dropping nodes out of a plane, the distribution of the nodes once touched down cannot be precisely predicted. When covering very wild areas with rocks, hills or a forestal area, the disturbances for nodes can be various. Some nodes might crash during the touch down process, other might fall into rivers and swim away. Others might land in disadvantageous places with lots of shielding objects around making it impossible to establish a radio communication. All these exemplary influences lead to a non-homogeneous distribution of nodes; typically with clustered topologies. It will also lead to unequal importance of nodes. Some might be redundant because they sit right next to a partner node – others might obtain a critical position being the only data relay for a large separated group.

B. Changes in the environment

When sensor nodes are deployed in a non-static environment, the connection topology will change over time. To gain more inside in this topic, we discussed with the responsibles from a European research project [6] over their experience during a several month deployment of a sensor network in a potato field [7]. For the topology and connectivity issues that we discuss in this paper, the most important message from this experiment was that the radio connections are very sensitive to rain and growing plants. At the beginning of the experiment, the potato plants very small and the sensor nodes distributed among them were well connected. Over time the plants grew and the connections became worse and worse and broke off at random points leading to an overall non-complete coverage.

C. Wear-out

When sensor networks are deployed for a long-term monitoring they carry an independent energy source. In the majority of cases they will be battery-powered. Therefore the lifetime of a single node is limited through the lifetime of the battery. At the end of the planned lifetime, nodes will start to die out and will no longer be connected to the system. Important relay stations that have stopped working will disconnect others from the access point and so on. In such a situation it is highly probably that partitioning of the network and separation of nodes will take place. Radio transmission power can also depend on the remaining resources of the battery attached. Low battery level simply causes less transmission range again resulting in bad connectivity.

D. Mobility of nodes

The last point to mention here is the most important one. If nodes in a network are mobile and the network is not supported by stationary relays and routers, the connectivity can vary even stronger than in the above described scenarios. Additionally, the changes will vary quickly over time. Mobile scenarios are e.g. the monitoring of a herd of wild animals, tagging of objects of animals swimming in rivers or seas, ice-clods or any similar effect from natural movement.

III. COOPERATIVE TRANSMISSION CONCEPT

Cooperative transmission is an ideal means to tackle the threads that are introduced by bad connectivity or sparse settings in general. With cooperative transmission, a group of nodes can combine its emission power and achieve a higher emission power as a whole. To do so, cooperatively transmitting nodes emit identical symbols synchronously to superimpose the emitted waves on the physical medium. The destination receives the sum of waves and thus a higher total power. The more nodes cooperatively transmit, the higher will the power on the physical medium be. With the higher power, the nodes can reach destinations that are very far away. Figure 1 shows two nodes with their emission range and the emission range of their combination.

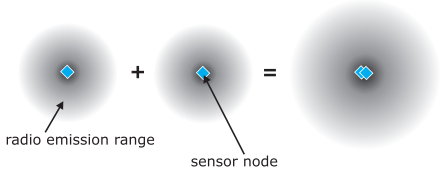

Fig. 1. Increasing the emission range by summation of the radio power

A. Related Work

In this paper, we want to discuss cooperative transmission under the constraint of very inexpensive sensor network nodes to achieve a power gain through summation. The sensor nodes transmit identical symbols simultaneously over the radio channel to sum up the total transmit power. The most related work can be found in [8] and [9]. In those publications, the authors understand cooperative transmission in the sense that several sensor nodes transmit symbols simultaneously to achieve a power gain. In [9] the broadcast-coverage of a system using cooperative transmission is analyzed. It is based on a continuum approach modeling the nodes as a homogeneous density of possible transmit power. This simplifies the modeling and leads to closed-form solutions and formulations. In [8] there is also a small section on the coverage achievable with cooperative transmission. We want to look deeper into the topic of coverage and connectivity for sparse settings using cooperative transmission. For the discussion of energy efficiency, we refer to [10]. [11] provides a good overview and comparison of broadcast-techniques for wireless sensor networks which is also relevant for this paper.

In this paper we are particularly interested how to deal with inhomogeneous settings caused by random distribution of nodes process like described in section II which we consider relevant for practical usage of cooperative transmission systems. The effects of e.g. the wear-out of critical relay stations or heterogeneous and inhomogeneous environments with unpredictable connections are major threads for the success of wireless sensor nodes.

B. Radio Propagation and Energy Model

We name P_{tx} the nominal transmit power of a node. We assume the transmit powers to be the same for all nodes. $P_{rx,j \leftarrow i}$ is the received power of a signal propagated from node i to node j. A receive power $P_{rx,j \leftarrow i}$ above a given threshold P_{th} will provide sufficient SNR in the receiver to decode the transmission.

For the channel model between two nodes i and j, we assume three influences on the wireless system: First, the path loss, which we model as a radial fading $\sim 1/r_{i,j}^{\beta}$. With this, we can give the nominal maximum distance for successful communication as $r_{th}^{\beta} = \frac{P_{tx}}{P_{th}}$. Further, as antennas of wireless sensor nodes are typically strip, printed, coil or simple dipole antennas and never have omni directional behavior, we assume a strong random symmetrical influence factor $\alpha_{i,j} \sim \mathcal{N}(1, 0.5)$ caused by the random orientation. For the channel, we assume a rayleigh-process through multi-path propagation. All factors together are the basis of the simulations in the following sections. For the cooperative transmission model, we assume that the power gain can be completely exploited. A group G of nodes all connected to each other can combine their powers and transmit towards a node j:

$$P_{rx,j \leftarrow G} = \sum_{i \in G} P_{rx,j \leftarrow i} \tag{1}$$

Assuming the mean connectivity, the expression including the mentioned factors (1) would be

$$P_{rx,j \leftarrow G} = \sum_{i \in G} \alpha_{i,j} P_{tx} \left(\frac{r_{th}}{r_{i,j}} \right)^{\beta} \tag{2}$$

As the discussion of the energy usage is not in the focus of this paper, we assume a very simple energy model. The model used throughout the remainder of this paper is that one transmission of a node takes a certain amount of energy E_{tx}. We do not consider power-control schemes for transmission of data between nodes. Neither do we consider low duty-cycle protocols and instead assume that nodes are awake all the time. Low duty-cycle protocols are not interesting for the connectivity discussion in this paper as the sleep times do not affect the overall connectivity – only the total delay. This additional power caused by listening is constant for all comparable cases and we therefore neglect it in the comparison. We give a short overview of interesting effects on the energy usage in section IV-B

C. Transport Scenarios

Different transport scenarios will be discussed and simulated in the remainder of this paper. We distinguish mainly two types of transport scenarios which we consider the most relevant for sensor networks: the *peer-to-peer scenario* and the *access point scenario*. In the latter, we assume that there is an access point – located in the middle of the sensor field – that has a very high transmit power directly reaching all nodes in the field. The nodes are low-power devices and cannot reach the access point in a single-hop manner. Additionally, the information flow is only between the access point and the nodes. Information exchange between nodes in a peer-to-peer manner is not foreseen. Communication with other nodes is only with the intention to relay packets to the access point. In this scenario a node is considered connected if it can forward or route a message towards the access point using whatever technique.

In the peer-to-peer scenario, we want to transport information between arbitrary pairs of nodes of the network realizing a mesh connectivity. This is e.g. useful if the information gathered with sensor is directly used in the network and the topology does not foresee an access point. Here, we call nodes connected when they are able to exchange information between each other using routing or cooperative transmission.

For all scenarios and protocols, we assume a continuously changing environment. The reasons for this were summarized in section II. For fast changing and unpredictable connectivity and topologies, there is a straight-forward solution that provides the best possible connectivity between any node: *broadcast communication*. As connectivity is the main concern in this paper we choose this communication for all following simulations and communication processes. For the multi-hop communication in the next section, this broadcast implies the use of *flooding*.

D. Communication Principles

To compare cooperative transmission to traditional approaches, it is necessary to clearly distinguish between different communication principles. Looking at sparse settings, which we focus on in this paper, it is clear that multi-hop communication reaches its capabilities when low node density causes partitioning and clustering of the network. In this situation cooperative transmission can help to "heal" the broken links. How to take advantage out of the possibilities that cooperative transmission provides is difficult to decide. The optimal power control for cooperative transmission scheme is e.g. an NP-hard problem [10]. Therefore, we want to discuss different pragmatic principles in the communication. For the comparison, we distinguish between four different types of communication principles:

1. traditional multi-hop communication (flooding)
2. wave propagation cooperative transmission
3. accumulating cooperative transmission
4. ideal hybrid multi-hop cooperative transmission

The following sections will discuss and explain a situation where a node (no. "0") wants to forward a message to a destination (no. "6") using the four different types of communication. Figure 2 shows the reference scenario. This scenario is an example for both transport scenarios. The node 6 could be the access point or an arbitrary peer. The small network in the example is heavily partitioned. Node 0 can only communicate with node 1 and there is another cluster consisting of nodes 3, 4 and 5. Node 2 and 6 are completely isolated. We assume no further knowledge about the topology for this transport

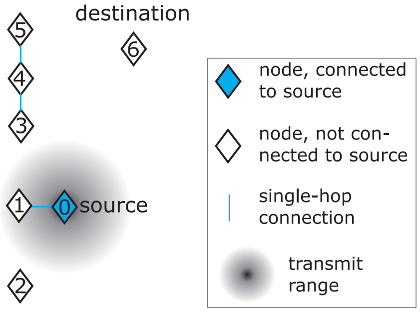

Fig. 2. The communication scenario: node 0 (source) wants to forward a message to node 6 (destination)

process. The nodes can be mobile and the connectivity may change over time. Therefore, we choose a straight-forward communication principle for all further scenarios: *broadcast communication*. The remainder of the section discusses the performance of the communication principles based on this scenario.

1) Traditional Multi-hop Communication: As shown in figure 2, node 0 can communicate to node 1 and vice versa. After node 1, the multi-hop communication is finished as the distance to the next nodes is to high. Node 0 can't find a multi-hop route to node 6 and therefore can't deliver its message.

2) Wave Propagation Cooperative Transmission: When nodes use the wave propagation cooperative transmission, each node will repeat a received message once. It will do this together with all other nodes who at the same time received the same message. This communication principle is very similar to the *opportunistic large arrays* in [8]. The message will propagate through the network like a wave-front. For our example this means that after the transmission of node 0, each node that received the message will repeat it once together with all others. Unfortunately, node 0 can only reach node 1 and therefore the transmission dies out after the second step.

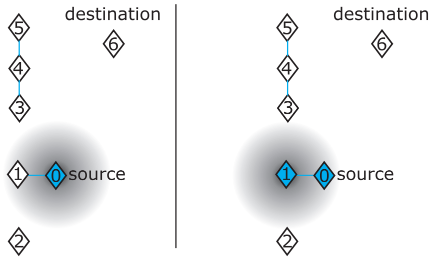

Fig. 3. The communication scenario using *wave propagation cooperative transmission*

3) Accumulating Cooperative Transmission: This principle is a slight modification of the previous *wave propagation cooperative transmission*. It is similar to the *cumulative increment algorithm* in [10]. Nodes that received a message will not only transmit this message once but several times. We set the number of repeats as a system parameter. Using this communication principle, we see the first gains in tackling the problem to deliver a message from node 0 to node 6. Figure 4 shows the situation for the first two steps. After node 0 has delivered the message to node 1, they both repeat the message simultaneously and this cooperative transmission leads to summation of energy (left side in Figure 4). The next two nodes (no. 2 and 3) can be reached. In the then following step, the group of cooperatively transmitting nodes includes the partners no. 0, 1, 2 and 3. Figure 5 shows the last two steps where node 4 and 5 are included (accumulated) in the cooperative transmission that finally all nodes except no. 6 transmit cooperatively. The sum of powers is then enough to finally reach to node 6. For this communication principle, the simple implementation for the *wave propagation cooperative transmission* also holds: For the delivery and relaying of packets, it is not necessary to keep track of connections and paths. Nodes simply repeat a message several times after reception.

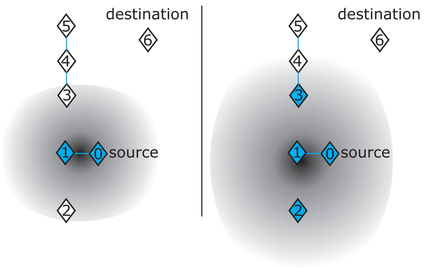

Fig. 4. The communication scenario using *accumulating cooperative transmission*

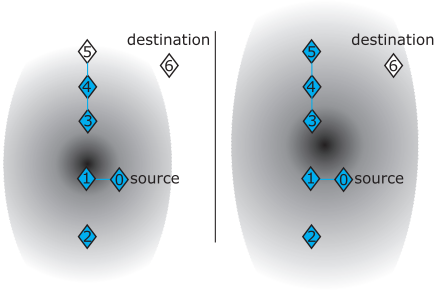

Fig. 5. The communication scenario using *accumulating cooperative transmission*

4) Hybrid Multi-hop Cooperative Transmission: The idea of this communication principle is to use multi-hop communication wherever possible and cooperative transmission wherever necessary. Depending on the topology of the communication links, this decision whether to choose multi-hop or cooperative transmission for the next communication step can be very hard to decide. If the next communication step should be cooperative transmission it is also hard to select the right nodes to exactly bridge the communication barrier. In mobile scenarios, this topology information can hardly or impossibly be generated. Therefore, we chose a pragmatic approach how we understand this hybrid communication principle. It is an *alternating* communication between multi-hop and accumulative cooperative transmission. After the cooperative transmission, all “new” nodes will try to acquire further partners using multi-hop and after this, a new *accumulated cooperative transmission* will take place with the now larger group. Whether a node is new or not to the actual group can be identified through the message sequence number of the message that has to be delivered. The time necessary for sufficient multi-hop communication between two steps of cooperative transmission will be unpredictable for the initiator node and must therefore be set to a certain value with a best-guess approach. It would then be understood as a deadline, such that the nodes would cooperatively transmit, then do multi-hop broadcast until a certain deadline and then starting over again with cooperative transmission. The number of iterations of this process would also be set by the originator and included in the message. The figures 6 and 7 explain the steps in detail. With the first multi-hop broadcast, node 0 has found node 1 as partner. With this partner, node 0 then cooperatively transmits the message. This is shown on the left side in figure 6. After this step, nodes 3 and 2 are "new" to the group and forward the message using multi-hop. These steps are on the right side in figure 6 and left side in figure 7. Then, as a consequence of the alternating process, all new partners and the old partners together cooperatively transmit the message again. This is shown on the right side in figure 7. This process continues then with alternating multi-hop and cooperative transmission until a predefined number of repeats is through.

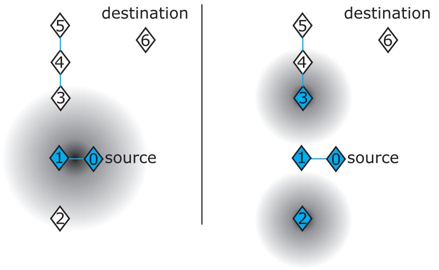

Fig. 6. The communication scenario using *hybrid multi-hop cooperative transmission*

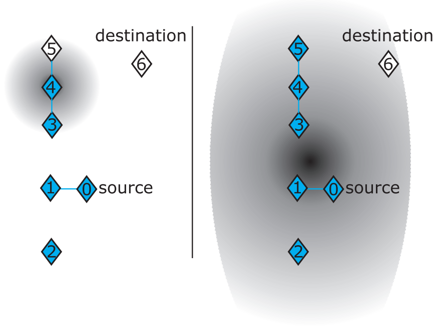

Fig. 7. The communication scenario using *hybrid multi-hop cooperative transmission*

IV. INCREASING THE COVERAGE

Using cooperative transmission, nodes can increase their radio range by combining transmit power with their neighbors. With this mechanism it is obvious that the overall coverage will be improved as lost nodes or clusters have a new way to establish a connection which is not possible without cooperative transmission. We simulated over 20000 random scenarios to illustrate the improvements that can be achieved with cooperative transmission. Without loss of generality we restrict the simulations to the access-point scenario: Nodes where uniformly distributed over the whole area, the access point is always positioned in the center of the area. Table I gives an overview of the technical parameters of the simulation. We simulated different communication principles which are now explained with reference to their names in figures 8 and 9:

- "multihop": this is the normal multi-hop scenario like it is used in traditional networks. Nodes forward and relay packets hop by hop. For the case of this paper we used *flooding*
- "acc.co.tr.1": this is the *accumulated cooperative transmission* principle. In this first level, a node transmits and its one-hop-distance partners (the first-level) nodes repeat the message together with the initiator using cooperative transmission. The process stops after one step
- "acc.co.tr.2": this is the same like the "acc.coo.tr.1" but now after the first step, the second-level nodes who received the packet will also repeat the message together with the initiator and the first level nodes
- "acc.co.tr.3": initiator, first-level, second-level and third-level nodes will repeat the message together using cooperative transmission
- "hybrid 1": here, the initiator broadcasts its packet using multi-hop communication. All nodes that are reached in this process will then transmit the packet using cooperative transmission
- "hybrid 2": after the transmission of the initiator together with its multi-hop partners, all reached nodes will collected all their multi-hop partners and then, all the reached nodes including the initiator, it's multi-hop partners and the multi-hop partners of the nodes that where reached in "hybrid 1"do a cooperative transmission

simulation area	500m x 500m = 250.000m^2
number of nodes	10..200
average nominal radio range	50m
fading exponent	$\beta = 2$
topologies for each number of nodes	100

TABLE I
SIMULATION PARAMETERS

Figure 8 shows the average percentage of nodes that are connected to the access point using the different communication principles. A connection to the access point means here that a node is able to forward packets from the node to the access point. The reverse way is not regarded as we assume a high power for the access point. In figure 9, the reverse way is also regarded. Here, a connection is only understood as valid when a bi-directional communication with the according communication principle is possible.

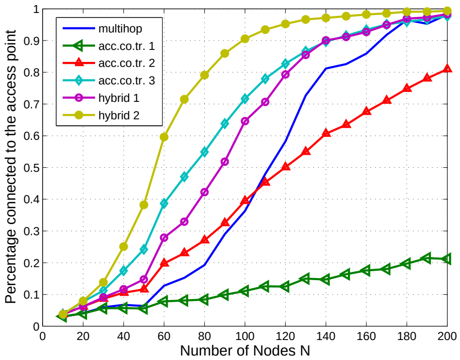

Fig. 8. Connectivity of Nodes towards their access point, area=500m x 500m, radio range ≈50m

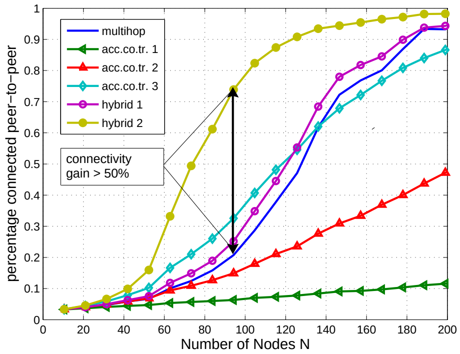

Fig. 9. Peer to peer connectivity of nodes

The best results are achieved by the hybrid protocols. This behavior is as expected: the hybrid protocols combines the advantages of both multi-hop and cooperative transmission and can therefore achieve the highest connectivity. On the other hand, the hybrid protocol is also the most complex for implementation.

Accumulated cooperative transmission performs very bad when only few levels are included. The differential (with respect to the node density) improvement in connectivity for the level one version of this principle is very weak. Also the overall connectivity to the access point is bad. The weak performance of level one is due to the reason that nodes only transmit using their one-hop partners ignoring the multi-hop communication possibilities. Nevertheless, after three levels of this simple communication principle, the multi-hop communication is outperformed when forwarding packets to the access point (see figure 8: "acc. co. tr. 3" performs better than "multi-hop"). In figure 9, a very interesting measure is displayed as an example of the advantages that cooperative transmission can contribute: It is the connectivity gain in sparse settings. When approx. 90 Nodes are present using traditional multi-hop, only 20% of the peer-to-peer connections are possible. This value cannot be further improved by any routing or other broadcast technique. But when using the new communication principle for the same scenario, over 70% of the peer-to-peer connections are active and can be used for data traffic improving the over-all connectivity by more than 50%! The next interesting measure is the number of nodes necessary to achieve a certain number of nodes to be connected to the access point. This is the question of over-provisioning or redundancy. If nodes are randomly distributed over a certain area, not all nodes will be connected to the access point. But if the connection of a certain number of nodes must be guaranteed, then it is necessary to deploy more than the minimum necessary number of nodes. In Figure 10 one can see the number of nodes deployed and the number of nodes that have connection to the access point. The theoretical border is clear: all nodes are connected to the access point. The line of the theoretical border is dotted below 100 nodes, because for our scenarios 100 nodes is the lower limit for a complete coverage of the whole area. With 100 nodes ideally positioned over the area and no variance in the transmit power, the area could be completely covered using multi-hop communication. But with 100 nodes and a random distribution process and additional variations in the transmit power, we can read out in figure 10 that only 40 nodes are connected to the access point when using traditional multi-hop. This means, that more than the 100 necessary nodes will have to be deployed to get a satisfying connectivity. For normal multi-hop (and the simulation parameters used in this paper) this number would be 130, meaning a 30% redundancy is necessary. The numbers can be found in figure 10: taking the graph for multi-hop and the x-value for 130, we see that the y-value is 100, which is the desired number of nodes with connection to the access point. When using the "hybrid 2" protocol, the necessary number of nodes to get 100 of them connected to the access point is only 110 nodes meaning a much smaller redundancy. For the same coverage in the same area with the same parameters for communication, the hybrid protocol needs less over-provisioning or redundancy. This will directly reduce the cost when deploying such a system.

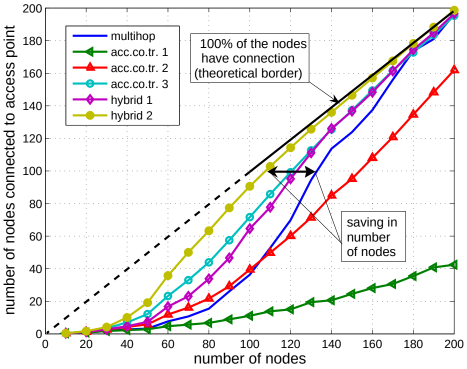

Fig. 10. Number of nodes connected to the access point

A. Limit Behavior

After having discussed the particular advantages in coverage and saving in necessary nodes, it is also interesting to see what the maximum possible gain with cooperative transmission is. For this, we simulated the same scenario using again *accumulating cooperative transmission* and *hybrid cooperative transmission*. We simulated different depths of these communication principles to be able to compare the gain that a certain level contributes. In figure 11 one can see the connectivity graphs for the different protocols and different levels. The first and most important finding from these simulations is that both protocols reach the same average limit connectivity for a given node density. That means, if the maximum possible connectivity must be reached in the system, it is finally is not a question of the specific protocol. But, the hybrid protocol reaches the limit already in the third level. This means that after three rounds of the hybrid process of multi-hop plus cooperative transmission, the maximum connectivity is already reached. More repeats do not contribute relevant improvements. For the accumulating cooperative transmission process, the approx. same performance is reached after six steps. On the first view, one would now conclude that the hybrid protocol is the clear winner. This is only partly true. The complexity of the process that is performed in each level or round of the hybrid protocol also includes a multi-hop broadcast. Hence the hybrid protocol – compared to the simple accumulating cooperative transmission – includes much more coordination and communication in each step. Therefore, the comparison of hybrid and accumulating cooperative transmission is somewhat improper. It is more a question of implementation than of performance.

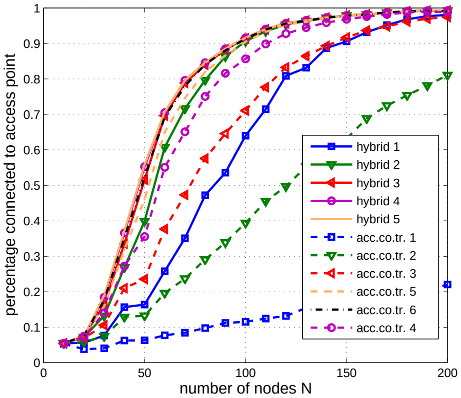

Fig. 11. Limit gain for cooperative transmission

B. Energy Consumption

As mentioned in section III-C, we assume broadcast communication for all packet transport processes with the energy model described in section III-B. As the energy discussion is not the focus of this paper, we only want to mention some general issues here. Hybrid cooperative transmission – which is the most powerful presented principle – has also the highest energy consumption. This is due to the alternating process of multi-hopping and cooperative transmission. After the first multi-hop process, the next cooperative transmission process will include all connected peers. Therefore the hybrid 1 scheme will double the necessary energy compared to the multi-hop broadcasting.

There is a general trade-off between connectivity and energy consumption. The more steps an accumulating or hybrid cooperative transmission scheme runs, the more energy will be consumed. On the other hand will more steps also increase the connectivity. For topologies with sufficient connectivity, multi-hop solutions are expected to perform more energy efficient. But for sparse settings, this low energy consumption also leads to a bad overall connectivity and investing more energy in multi-hop communication cannot help to increase the connectivity. For the cooperative transmission principle, this relationship looks different: investing more energy in the communication helps to improve the connectivity. This statement is particularly true for the application of cooperative transmission in sparse settings.

V. EXPERIMENTAL IMPLEMENTATION

With the particle computer [4] pPart hardware we built the – to our knowledge – world's first hardware implementation of cooperative transmission. The pPart platform has the advantage, that the RF base-band signal can be accessed and a detector can be implemented in software. We processed the base band signal at 35kHz and implemented an energy detector and the signal modulation in software (see [12] for theoretical details). The experiment in figure 12 included four pParts on one side and one pPart on the other side. The four wanted to send a signal cooperatively to the partner node on the right side. We selected how many should send at the same time to see the advantages of the cooperation of the nodes. We did 100 single experiments with one, two, three and four pParts sending a signal cooperatively and counted the successful receptions. With this experiment we show that the concept of adding transmit powers together is feasible

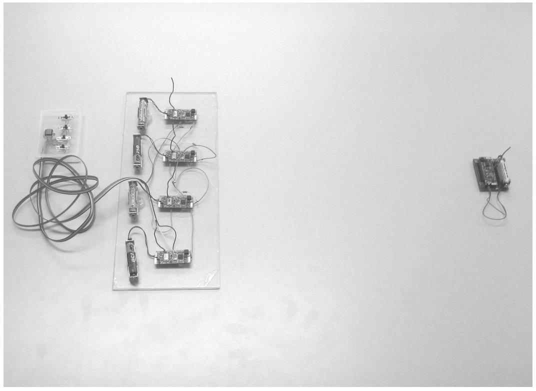

Fig. 12. The experiment with pPart particle computers

and realistic. Table II shows the detection results. P_d ist the detection rate of the experiments; P_f are the false alarms. The contribution of cooperative transmission is obvious: with one and two pParts sending, the power is just not enough. But when three or more send, the signal can be detected by the receiver. It also shows, that the built-in ASK- threshold detector in the TR1001[1] radio transceiver used in the pParts is inferior to our software implementation of the non-linear energy detector.

number of pParts transmitting ccoperatively	P_d (non-linear energy detector)	P_d (TR1001 built-in threshold detector)	P_f
1	0	0	0
2	0	0	0
3	0.97	0.09	0
4	0.97	0.93	0

TABLE II

COOPERATIVE TRANSMISSION EXPERIMENTS WITH PPARTS

VI. CONCLUSION

Cooperative transmission can improve the connectivity of nodes toward other nodes or an access point especially in sparse settings. In section II we collected some arguments how sparse settings arise and why they cannot be avoided in all cases. Cooperative transmission can support especially topologies of clustered and partitioned networks that contain separated groups of nodes. Using cooperative transmission, a separated group can jointly transmit a message with higher transmit power reaching the otherwise unreachable partner nodes. *This effect is a contribution of cooperative transmission, that otherwise cannot be accomplished by normal multi-hop.* This new communication principle can overcome connectivity problems in sparse settings or heavily partitioned topologies. Looking back on the limit performance analysis in figure 11, the hybrid protocol is the one with the fastest convergence towards the optimum. On the other hand, it is much harder to be implemented. In table III, we compare use cases and implementation effort of the mentioned communication principles. For a practical implementation, the *accumulating cooperative transmission* seems to be a very interesting candidate. With the level 3 version of this protocol, we can already achieve a comparable performance to multi-hop with as well a comparable energy effort. But the cooperative transmission protocol keeps the possibility to be extended to level 4, 5 and so on to increase the overall connectivity. Multi-hop communication is instead limited to its one-hop mesh connectivity. The implementation of cooperative transmission is very easy and can be stateless and without routing tables or similar connectivity lists. For wireless sensor networks cooperative transmission can also be applied as a fall-back solution only. For that case, the network would perform normal routing, broadcast and multi-hop protocols with the necessary properties. Only in cases where nodes find themselves unconnected as a separated group, they would perform a cooperative transmission. For this system design, cooperative transmission would selectively be evoked as a solution when traditional processes cannot overcome the connectivity problem in a sparse setting or partitioned network.

protocol	implementation effort	target scenario and application
multi-hop broadcast (flooding)	medium	dense settings static scenarios
wave propagation cooperative transmission	low	dense settings broadcast traffic
accumulating cooperative transmission	low	sparse settings static, mobile scenarios
hybrid cooperative transmission	high	sparse settings static scenarios

TABLE III

COMPARISON OF COMMUNICATION PRINCIPLES

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