Energy-Balanced Cooperative Routing Approach for Radio Standard Spanning Mobile Ad Hoc Networks

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Abstract— **In this paper, a new Energy-Balanced, Cooperative Routing approach (EBCR) for radio standard spanning mobile Ad Hoc networks (MANETs) will be introduced and evaluated. Past research approaches are limited to the usage in homogeneous topologies on basis of a unique radio standard. The proposed reactive EBCR provides an efficient routing of data in heterogeneous multi-standard network topologies. In addition to an improved reachability, a primary objective is to balance the overall power consumption in each operating node to prolong the lifetime of the whole topology. Instead of using static cost factors for the route path calculation, EBCR integrates a dynamic cost vector for the handling and processing of a data packet. This includes parameters like the required field strength for the data transmission and the node's current energy level to calculate the cooperative, optimal route path. Thereby, EBCR operates only on the basis of local network information. For evaluating the conceptual advantages of this approach, multiple scenarios with static and high-dynamic network topologies have been analysed in a dedicated simulation environment. The simulation results verify the significant improvements in the topology lifetime and the reachability up to 15%.**

I. INTRODUCTION

An optimal mobile Ad Hoc network can be characterised by a good distribution of net load over all nodes, a good scalability and the robustness against disturbances and partial losses. Due to different application areas of wireless communication networks in industrial and private environment a multiplicity of radio standards has been developed. Each standard has application optimised characteristics in regard to transmitting range, data transfer rate, power consumption and the used frequency band. Almost every radio standard uses link-based transmission techniques to send and receive data. Accordingly, capable methods for the routing and forwarding of data packets between different network nodes are necessary. The current approaches for connectivity and communication in wireless mobile Ad Hoc networks are, however, only occupied with one radio standard each. The radio standard spanning interaction is not possible.

Looking forward to the next generation of wireless mobile technologies, one essential ability will be the integration of different wireless communication standards. *Figure I* illustrates related wireless communication techniques, represented by IEEE 802.x protocol standards, for different application areas and transmitting ranges [1]. Optimised 4G wireless mobile technologies must provide a interoperability between these application areas to create a multi-standard heterogeneous network topology.

One central point of such a concept is an efficient, radio standard spanning routing algorithm, which allows a reliable, fast and adaptive data packet transport in the available network topology. This paper presents a energy-balanced, cooperative routing approach (EBCR) to offer an abstract solution. After this introduction, section *II* will give an overview on past publications in the research fields of routing in mobile Ad Hoc networks, wireless multi-standard communication and interface synthesis. The following section *III* offers detailed information about the EBCR algorithm. Some key facts about the simulation environment are summarised in section *IV* and, later, relevant definitions for the cost function and scenario-specific weighting schemes are presented. Accordingly, the received simulation results are discussed in section *VI*. Finally, the paper concludes with a summary and an outlook for future work in this research area.

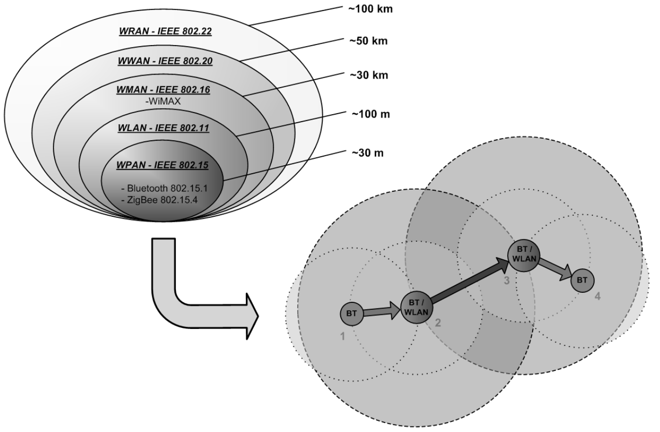

Fig. 1. Illustration of the serveral wireless communication standards IEEE 802.x with optimised characteristics for different transmitting ranges. Next generation wireless networks (bottom right) integrate different radio standards into one heterogeneous topology

II. RELATED WORK

Based on a dynamically optimised topology, data between arbitrary nodes can be transmitted in the network. For the efficient package-oriented data communication, routing algorithms are used, which lead the packets over a preferably optimised path to the destination node [2]. For the usage in mobile Ad Hoc networks, proactive routing algorithms have been developed, which try to update a local routing table also in a dynamic network topology. Thus, valid route paths are already found before they are needed for communication. At the time of a communication request, each node has a current route, without causing latencies. A representative of proactive routing algorithms is the Optimised Left State Routing (OLSR [3]) or the Destination-Sequenced Distance-Vector Routing (DSDV [2]). Since the administration complexity of such routing methods strongly rises with increased dynamics, reactive routing protocols have been conceptualised, which search valid route paths not until there is a connecting request (Ad hoc On demand Distance Vector AODV [2], Dynamic Source Routing DSR [2]). Also hybrid algorithms, like the Zone Routing Protocol (ZRP [4]), have been developed.

Xia et. al. propose in [5] an interesting approach to increase the lifetime of a wireless sensor network by the integration of a node's actual energy level into the routing algorithm. So this gradient-based routing protocol prefers route paths with a high energy level of the several nodes. This enables an self-adjusting balance of the energy consumption in the whole topology. The approach has its focus on the application field of wireless sensor networks with a uniform radio standard. The typical network traffic scenario is a balanced, periodical transmission of sensor data.

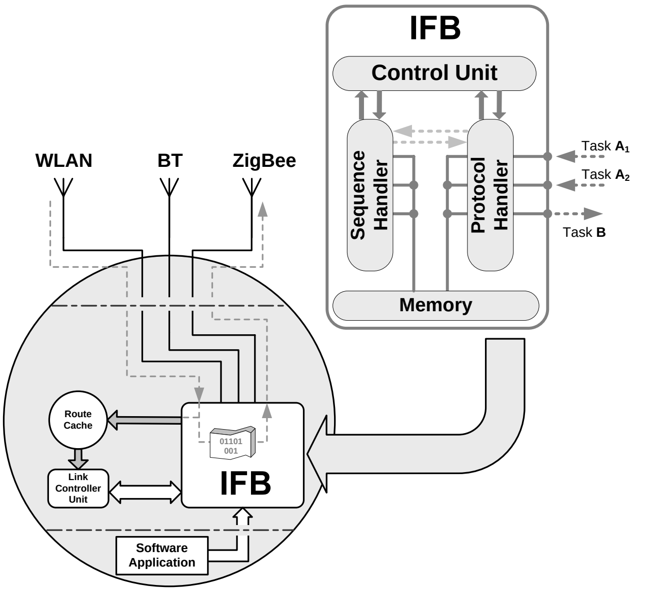

Fig. 2. The Interface Block (IFB) Macrostructure (top right corner) with Control Unit, Protocol Handler and Sequence Handler. Two tasks A (with the subtasks A_1 and A_2) and B with incompatible protocols communicate with each other using the IFB. In the bottom left corner the Basic layout of a radio standard independent node. Exemplary with three antennas for the radio standards Wireless LAN, Bluetooth and ZigBee. A central IFB connects the radio modules. Based on cached routing information, the link controller unit (LCU) manages the data flow in the IFB. Software applications use only one well-defined interface to the hardware block.

To achieve a radio standard spanning communication in MANETs, one central challenge is the interaction between the communication standards with different protocols. A promising solution for a this problem is the hardware-near coupling of individual standardised radio modules. For this purpose a special hardware block, which provides a conversion of incompatible protocols, is necessary [6][7]. Such an interface block (IFB [8]) analyses incoming packets and extracts the user data. Subsequently, these data are adapted on desired protocols and passed on accordingly. Due to the IFB macro structure (*Figure 2*) a modular expandability is ensured.

Based on the IFB approach, a concept for the radio standard spanning communication in MANETs was proposed in [9]. The individual nodes (*Figure 2*) of a network topology can use advantages of different radio standards to get a higher degree of connectivity. They do not need a high arithmetic performance like it is necessary in research approaches of software defined radio [10][11]. An energy-efficient and multi-functional applicable possibility of wireless communication is created. The presented approach is divided into three primary objectives, which have to be solved: topology construction, protocol conversion and routing. In the following sections of this paper an efficient routing algorithm will be introduced and analysed.

III. COST VECTOR-BASED COOPERATIVE ROUTING

In order to provide a routing algorithm, which is able to make decisions about the choice of the used radio standards and the optimal route path on the basis of functional connection requirements like required bandwidth or available energy resources, the EBCR was developed. The primary objective is the integration of multiple cost indicators in a dynamic cost vector to prolong the average node lifetime in the network topology. Parameters about the actual node status permit a cooperative choice of the route paths.

Basic Information

For the primary usage in applications of mobile miniature devices, which have strongly limited energy resources and usually small arithmetic performance, a reactive routing algorithm is preferred. EBCR is able to minimise the resources for storage and administration of routing information in the devices. Furthermore, EBCR does not need any global network information like the actual node position or movement parameters. Every node in the network sends a periodic heartbeat signal to allow the administration of lists with the direct attainable neighbourhood. On the basis of these local network information and some basic status parameters, EBCR creates a dynamic cost vector for the route path calculation.

In consequence of the primary aim of EBCR, the generated route paths are not hop-optimal in many cases. The approach prefers energy-efficient route paths, which prolong the reachability and the lifetime of the entire network topology by balancing the energy level of each node regardless of the available radio standards. Due to the combination of cooperative characteristics of wireless sensor network applications and related routing approaches for MANETs, an optimal usage of the available resources can be ensured.

Figure 3 illustrates a simple routing scenario from the source node A to the sink Z. There are three possible route paths, which generate different costs. By the fact that node B has a very low battery charge, EBCR will avoid this choice. For the decision about the route path via C or D, EBCR calculates the required transmission costs based on the radio standard, the required transmitting power, a possible swap of the radio standard (for example in node C during the path $A \rightarrow C \rightarrow Z$) and additional functional connection requirements.

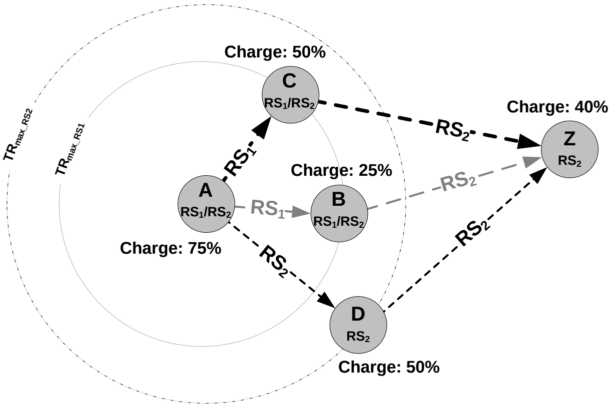

Fig. 3. A simple routing scenario with three possible routes from the source node A to the sink Z. Node A, B and C integrates two different radio modules RS_1 and RS_2 with specific maximum transmitting ranges $TR_{max\_RS_1}$ and $TR_{max\_RS_2}$. Node D and Z have only one available radio standard.

To balance the disadvantages of reactive routing methods like broadcast storms and in consequence radio interferences on the physical layer, EBCR provides the possibility of a counter-based retransmitting scheme [12] and a randomised retransmitting delay T_{b_delay}.

Broadcast/Forward process

With every route inquiry, the source node broadcasts the request including a unique time stamp. Each broadcast packet has a unique time stamp for a identification of equal broadcast messages. The several nodes caches these broadcast IDs and allows only a limited number of rebroadcasts over the selected radio modules. These simple techniques reduces the packet transmission error rate by radio interferences significantly [12]. Each node, which receives the request, updates the cost vector with the own parameter. In a defined waiting period T_{r_req} the node receives alternative sub-paths and compares the cost vectors. If the new cost vector is better than the stored one, the node updates its own route parameters. Bad sub-paths will be rejected. After T_{r_req} is expired and the maximum number of equal incoming broadcast request is not reached (counter-based retransmitting scheme [12]), the node rebroadcast the stored cost vector with the best parameters. If a broadcast request will be received by the sink node, the sink sends a corresponding response packet along the received route path. For the following bidirectional communication between the source and the sink, each node knows the next hop of the route path to forward the data packets. If the sink is not reachable, each node has a predefined timeout for broadcast requests. To reduce the number of route requests in the topology, valid route paths are temporary stored in a route cache with a maximum lifetime before they will be deleted. EBCR allows the additional caching of alternative route paths over different radio modules to provide backup functionality during a data transmission.

IV. SIMULATION ENVIRONMENT

Due to the designed cost vector model and the IFB-based integration of multiple radio modules, the usage of related network simulators like NS2 is not possible. To clarify the necessity of such a heterogeneous, interoperable communication concept, a modular, platform-independent simulation environment was designed and implemented for the proof of concept. Every network node is emulated by a dedicated thread with own defined parameters and properties. Thus, the simulator is scalable to different node densities and topology scenarios. An event-driven graphical user interface allows the visualisation of topology modification in realtime. To analyse the dynamic of mobile Ad Hoc networks, a movement model (*Random Waypoint Mobility model - RWP* [16]) was implemented. A global topology control layer provides a statistical interpretation of the entire network topology. An essential difference to other approaches is the possibility to configure network nodes with more than one interacting radio modules, which are controlled by the Link Controller Unit (LCU) and the IFB (*Figure 2*).

To evaluate the conceptual advantages of a radio standard spanning communication in MANETs, a complexity model on basis of cost vectors was developed. Thereby, each transmission of data generates costs that are dependent on the used radio standard and the transmission range. During the route path of a data packet to its destination node, a change of the communication standard also generates costs for the data conversation by the node's internal interface block. The several parameters of the cost vector are predefined uniformly and are adaptable in a topology. Based on these cost vectors and the usage of TCP/IP, the modified EBCR algorithm finds cost-optimal route paths in the network. The simulator does not have a physical calculation model for interferences in the used frequency bands. To avoid such disturbances and problems like broadcast storms, the EBCR algorithm provides a feature for a randomised packet forwarding delay as described in section *III*.

Each node has predefined energy resources, which provide a limited lifetime. Furthermore, the simulation environment provides the possibility to generate a periodic, basic power consumption for nodes in the idle mode. For the proof of the EBCR approach, this time-based feature is disabled. If the available resources are expired, the node switches its current operational mode to offline and is no longer available in the topology.

To evaluate the advantages of EBCR, several test scenarios were analysed. The following simulation results include topology scenarios with uniform and random node distribution (*Figure 4*) and two node densities of 30 and 60 nodes. For all scenarios, the maximum number of interacting radio modules has been restricted to the amount of two. It must be pointed out, that the theoretical maximum number of integrated radio standard is not limited upwards with the proposed concept. Each node has an initial battery charging state of 100% and one or two radio modules for the notional radio standards RS_1 and RS_2. $TR_{max\_RS_1}$ represents the default low-power radio module. The transmission range of the second radio standard $TR_{max\_RS_2}$ is predefined with $TR_{max\_RS_2} = 2 \cdot TR_{max\_RS_1}$. For the chosen test scenarios, 50% of the nodes has two available radio standards. The other 50% transmit with only one radio standard RS_1. In several test cycles the simulator generates randomised network traffic with a uniform or random number of data packets per message.

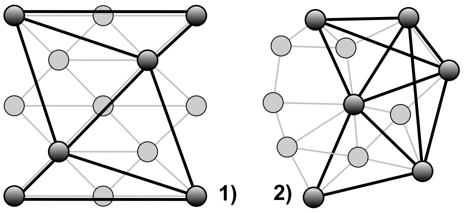

Fig. 4. Two exemplary network topologies with a uniform distribution (net 1) and a randomised distribution (net 2). Both topologies have about 50% of multi-standard nodes.

V. SIMULATION SCENARIOS

Cost vector definition

PARAMETER	RS_1	RS_2
Basic Costs per Hop C_{base}	20	20
Current Energy Level C_{e_level}	1-10	1-10
Transmitting Power Consumption C_{tpow}	0.8-8	5-50
Overall Data Transmission Time C_{ttime}	2-20	0.1-1
Data Packet Latency C_{lat}	20	10
Swap radio standard C_{swap}	10	10

Table I. Two defined radio standards with the separated costs for each factor.

For the proof of concept there are only two notional radio standards RS_1 *and* RS_2 with specific communication characteristics available. On the basis of these characteristics, *table I* describes the several parameters of the EBCR cost vector for the handling and processing of data. The three parameters C_{e_level}, C_{tpow} and C_{ttime} are defined in an interval. The individual values are calculated in each node as follows:

$$\begin{aligned} C_{e\_level} &= \frac{1}{P_{current}}, 0.1 \leq P_{current} \leq 1.0 \\ C_{tpow} &= 1 + (C_{tpow_{max_{RS_x}}} \cdot P_{transmit}^2) \\ & \quad 0.1 \leq P_{transmit} \leq 1.0 \\ C_{ttime} &= C_{ttime_{max_{RS_x}}} \cdot P_{transmit} \\ & \quad 0.1 \leq P_{transmit} \leq 1.0 \end{aligned}$$

$P_{current}$ ... node's current energy level
$P_{transmit}$ ... required transmitting power level

Accordingly, based on these cost factors, a cost function is defined as follows:

$$\begin{aligned} C_{overall} &= \sum_{i=1}^{\#_{hops}} (\sum_{j=1}^{n} (w_j \cdot C_j)) \\ &= \sum_{i=1}^{\#_{hops}} (w_{base} \cdot C_{base} + w_{e\_level} \cdot C_{e\_level} \\ & \quad + w_{tpow} \cdot C_{tpow} + w_{ttime} \cdot C_{ttime} \\ & \quad + w_{lat} \cdot C_{lat} + w_{swap} \cdot C_{swap}) \end{aligned}$$

n ... number of parameters
w_x ... weighting of parameter x

Cost vector weighting

By the usage of individual weighting factors, the cost function is adaptable to different fields of application. For the chosen simulation scenarios, the weighting W_{S1} is defined as follows:

W_{S1} ... power consumption optimised testing scenario

WEIGHTING PARAMETER	W_{S1}
w_{base}	1.0
w_{e_level}	1.0
w_{tpow}	0.6
w_{ttime}	0.3
w_{lat}	0.1
w_{swap}	1.0

Table II. The defined weighting scenario is based on the defined cost function $C_{overall}$.

Energy adaptation model

Each process for the handling and transmission of data decreases a node's energy resources dependent on parameters like the used radio standard or the required electromagnetic field strength for reaching the selected node. The initial charge state of each node is assumed with 10000 logical units. The function for the adaptation of the energy level ΔP_{node} is defined as follows:

$$\begin{aligned} \Delta P_{node} &= f(M, P_{transmit}, RS_x) \\ \Delta P_{node} &= \#_{packets} \cdot P_{transmit}^2 \cdot g(RS_x) \\ g &: (RS_x) \rightarrow N \\ g(RS_x) &= \begin{cases} 1, \text{Transmission } RS_1 \\ 6, \text{Transmission } RS_2 \end{cases} \end{aligned}$$

M ... Message size in packets
$P_{transmit}$ ... Required transmitting power level
RS_x ... Used radio standard

VI. SIMULATION RESULTS

The following results are divided into two subsection for uniform and random node distribution (*Figure 4*). For each distribution there are two simulation scenarios.

Topology lifetime scenario:

The first scenario chooses randomised source and destination nodes and tries to find a valid and optimal route path. Through every valid route path a traffic generator transmits a message with a predefined number of data packets. The simulation ends if no more node is reachable and all available energy resources are exhausted. The simulator counts the number of successful transmitted data packets in the topology and, accordingly, the number of dead or isolated nodes.

Static end-to-end scenario:

The second scenario simulates a static communication stream between two predefined nodes. After each successful transmission of a message with n data packets, EBCR calculates a new optimal route path to balance differences of the energy level in topology. A primary objectives of this scenario is to minimise the number of dead nodes to preserve a fully connected topology in which every node keeps reachable. The number of transmitted data packets must be maximised. *Figure 5* illustrates these objectives.

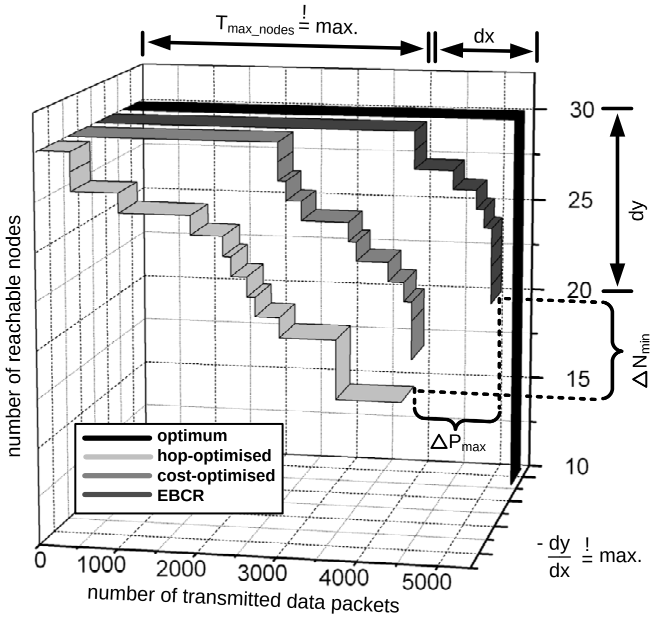

Fig. 5. The diagram shows the simulation results of three different routing approaches in a random distribution of 30 nodes. The theoretical optimum is illustrated as the black line. A primary goal is the maximisation of the time when all nodes in the topology are available (T_{max_nodes}). Simultaneously the negative slope of the curve must be maximised. An important measurement are the variations of the transmitted data packets (ΔP_{max})with several routing approaches. Differences in the minimal number of available network nodes (ΔN_{min}) are meaningful for all test cycles of the second scenario with a static source and sink.

As already mentioned in section IV, each process for the data processing and transmission decreases a node's energy level. In this simulations, two major processes influence this resource. Regardless from the result of a route request, each inquiry decreases the energy level of the reachable nodes as a consequence of the broadcasting process. If EBCR has found a valid route path, the generated traffic must be handled and forwarded in each node of the route path. Every data packet decreases the available energy resources dependent on the selected radio standard and the required transmitting power.

To verify the conceptual advantages of this approach, the lifetime of a valid route in the route cache is defined very short. With this precondition, the nodes in the topology are forced to use the routing algorithm for each transmission inquiry. EBCR is compared with two related routing approaches. The first one is a simple hop-optimised routing, which chooses route paths with minimum number of hops between source and sink. The second routing algorithm calculates an optimal route path with a non-cooperative, static cost function, which does not consider a balancing of the available energy resources or a node's current energy level. The several cost parameters are equal to the used parameters of section *III*.

Results - Uniformly Distributed Topology

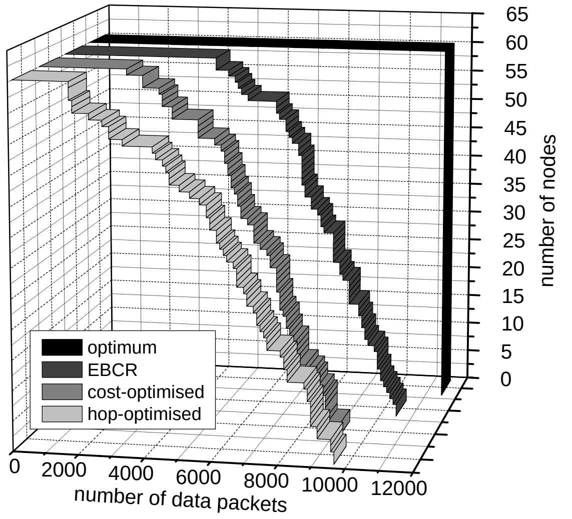

Fig. 6. Topology liftime scenario: uniform node distribution, 60 nodes, 50% of multistandard-nodes, message size: 100 packets

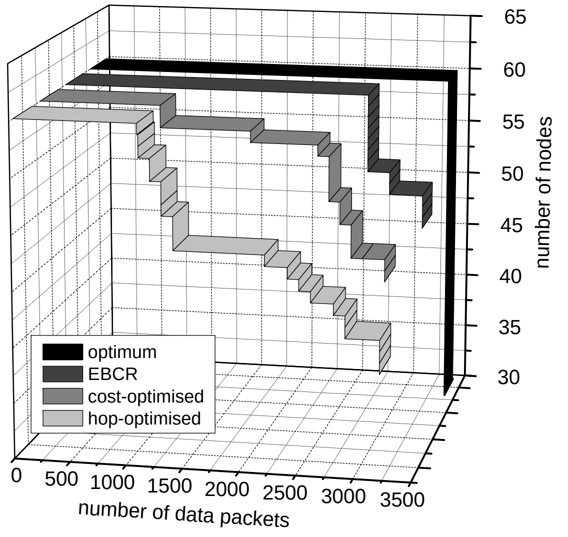

Fig. 7. Static end-to-end scenario: uniform node distribution, 60 nodes, 50% of multistandard-nodes, message size: 100 packets

Figure 6 illustrates the significant extension of the successful transmitted messages till the first nodes dropped out. Furthermore, with EBCR, the overall transmitted network traffic was increased of about 1000 data packets. An even higher degree of improvements shows the simulation results in the static end-to-end scenario. The EBCR curve in *Figure 7* is very close to the theoretical optimum. In addition, the number of dead nodes with depleted energy resources was reduced from 21 (hop-optimised routing) to 12, which is equivalent to an improvement of 15%.

Results - Randomly Distributed Topology

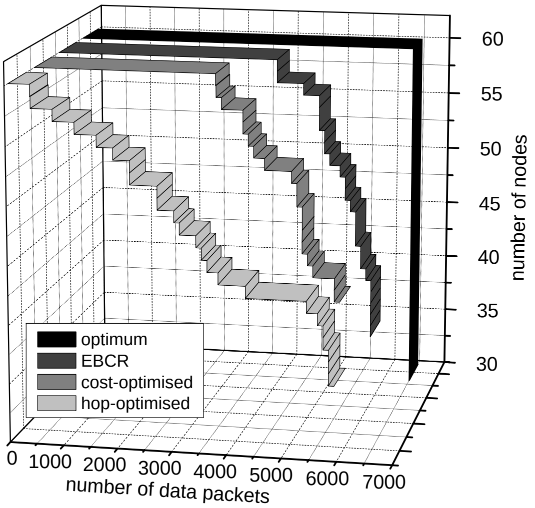

Fig. 8. Static end-to-end scenario: random node distribution, 60 nodes, 50% of multistandard-nodes, message size: 100 packets

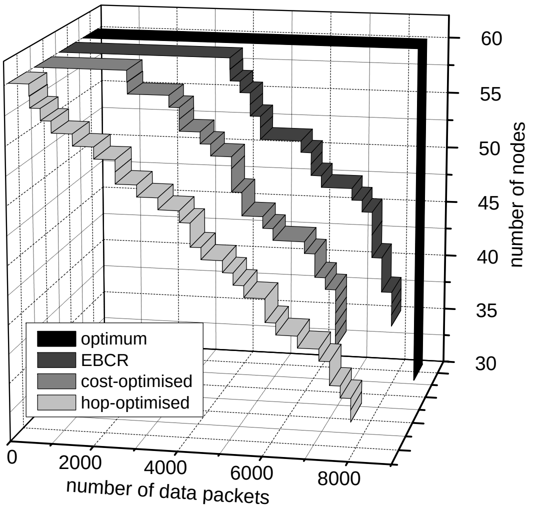

Fig. 9. Static end-to-end scenario: random node distribution, 60 nodes, 50% of multistandard-nodes, message size: random from 50 to 500 packets

Figure 8 and 9 represent the dependency on the simulation results from the defined message size. The simple hop-optimised routing approach shows a very high number of nodes with depleted energy resources in the second test cycle with a randomised message size. Independent on the defined packet size, EBCR provides the best results in the number of transmitted data packets. Furthermore, the simulations verify the primary objective of EBCR to maximise the reachability of each node in the topology.

VII. CONCLUSION

The presented simulation results clarify the importance and the significant advantages of this cooperative routing approach. The choice of the used routing algorithm is essential for a sufficiently stable, adaptive and scalable network topology. EBCR realises a radio standard spanning routing. This offers completely new possibilities for an efficient communication in high-dynamic MANETs. With an outlook to the next generation of wireless mobile technologies, EBCR provides a basic concept to integrate a multiplicity of radio standard into a single heterogeneous network topology. This enables various new application scenarios with wireless communication techniques.

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