Energy Saving Router Rotation Protocol for DECT-2020 NR

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***Abstract*—ETSI DECT-2020 New Radio (NR) is a new flexible radio interface targeted to support a broad range of wireless Internet of Things (IoT) applications. It has been shown to fulfill both massive machine-type communications (mMTC) and ultra-reliable low latency communications (URLLC) requirements for 5th generation (5G) networks. DECT-2020 NR is an autonomous wireless mesh network protocol where the devices can choose to become routers, forwarding the data of other devices in addition to their own data. Thus, a wireless mesh network does not need separate base stations or a core network architecture to extend coverage. This makes the deployment of DECT-2020 NR networks easy, but with the cost of increased energy consumption in the router nodes. Notably, the same energy consumption is not inflicted upon the non-routing leaf nodes whose operation is on the contrary very energy efficient. This role-induced disparity in node energy consumption results in the network not using the energy of its devices with maximal efficiency. A method to alleviate this problem could be a network rotation in which the roles of network nodes are periodically rotated and the energy consumption is thus distributed more evenly among the nodes. In this paper we propose a role rotation protocol for DECT-2020 NR and evaluate its impact to the expected lifetime and the performance of the network by system level simulations.**

Keywords—DECT-2020, NR, 5G, energy saving

I. Introduction

The DECT-2020 NR standard was released by the European Telecommunications Standards Institute (ETSI) in 2020 [1]. It is intended for industrial Internet of Things (IoT) applications requiring either massive machine-type (mMTC) and/or ultra-reliable low latency (URLLC) communications.

DECT-2020 NR introduces a device-based cluster-tree wireless mesh network (WMN), capable of forming an autonomous network without the need for separate base stations or core network. Nodes are capable of acting as routers between their neighbors, forwarding data between them in case direct connection is not possible.

WMN coverage can theoretically reach extreme distances with minimal costs and effortless deployment. However, forwarding data through the network with a reasonable delay requires that each node passing the data onwards has an acceptable duty cycle, meaning the node is able to receive and transmit reasonably often so that the delay requirements are met and the data does not accumulate to relaying nodes. However, maintaining an active duty cycle consumes energy resources which may be scarce if the network consists of mainly battery-operated nodes, as is common in the IoT domain.

Energy consumption is a well-known and well-studied problem of WMNs. Comprehensive surveys of different energy-efficient routing protocols proposed for wireless sensor/mesh networks have been presented in literature e.g. [2], [3]. The advantages and disadvantages of each considered algorithm has been quite extensively analyzed. However, no earlier work on the suitability or the performance of WMN energy saving protocols with DECT-2020 NR yet exists.

The performance of DECT-2020 NR has been evaluated earlier e.g. in [4]-[7] but none of the studies gave consideration to the network energy consumption. In [8] it was demonstrated that especially when serving delay sensitive data, the lifetime of a battery-operated DECT-2020 NR network is limited by the energy consumption of the router nodes, due to their active duty cycle required to maintain low latencies. On the other hand, the leaf nodes of DECT-2020 NR were shown to be very energy efficient as they only need to be awake intermittently. Due to this disparity in energy efficiency, it is evident that if the DECT-2020 NR network could distribute the energy consumption more evenly between the nodes, the network lifetime would increase.

More even energy consumption distribution can be achieved via node role rotation. The idea has been proposed for WMNs earlier in [9] where the authors proposed a Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol. LEACH utilizes a randomized rotation of cluster-heads, which are elected head nodes of local sensor node clusters. Cluster-heads collect the data from the nodes in the cluster, aggregate it and transmit it to the target base station, so their function is roughly similar to DECT-2020 NR routers. A cluster-head node consumes more energy than a regular node so in LEACH the cluster nodes periodically elect a different node to act as a cluster-head to evenly distribute the energy load.

Similar role rotation idea was also used in [10], where the Span algorithm was introduced for 802.11 ad hoc networks. In

Span, each network node periodically makes an independent decision on whether to sleep or stay awake as a coordinator node which is a similar node as DECT-2020 NR router node in a sense that it participates in forwarding the packets through the network.

Based on the findings of these earlier WMN studies one can expect network lifetime benefits from rotation also with DECT-2020 NR standard but exactly how much benefit is achievable cannot be concluded without implementing a rotation protocol that can be fitted into the standard and evaluating its performance using realistic modeling.

Compared to conventional WMN technologies, the energy efficiency of DECT-2020 NR is improved by the use of state-of-the-art physical layer techniques, such as Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM), turbo coding and Hybrid ARQ (HARQ) and periodic Random Access Channel (RACH) duty-cycling. These features make the comparison with earlier, more simpler WMN technologies difficult and justify the need for a new study.

In this paper we adapt the WMN role rotation functionality to DECT-2020 NR and propose a simple protocol to rotate the roles of network nodes without the need of specific election processes or central coordination but by merely reusing the mesh network organization process inherent in the standard.

Finally, we evaluate the actual effect of rotation to DECT-2020 NR network lifetime and performance by conducting dynamic system level simulations in a typical IoT use case with mesh networks of different sizes. The results of the study can be used to improve the energy efficiency of DECT-2020 NR standard in future releases.

II. DECT-2020 NR MESH NETWORK ORGANIZATION

The DECT-2020 NR network organization process is explained in the standard [1]. For a single network, there is always one sink, i.e. a gateway node to the Internet. There can be multiple sinks in a group of nodes but from the system point of view the sinks form their own networks (cluster trees), which co-exist but operate independently from each other. In this study we concentrate on the operation of a single network entity under one sink.

A diagram of the initial organization process in a simple network is presented in Fig. 1. The process starts by the sink selecting FT (Fixed Termination point) mode. In FT mode, a node first performs background (BG) scanning, searching for the least busy channel for operation. After finding a channel, the FT starts cluster beacon transmissions on it.

All other nodes are in PT (Portable Termination point) mode, where they initially scan channels for cluster beacons and after detecting one or more of them, select from them the sender FT for association. A PT having multiple FT candidates makes the choice based on the *route cost,* a parameter of the route info information element (IE) of the cluster beacon message. The specification mandates that each hop should increase the route cost by at least 1 but otherwise the exact route cost calculation is left to implementation so essentially the node is free to use any information available. Selecting a proper route cost metric is essential for ensuring the occurrence of role rotation in the network. We will discuss this more in section III.

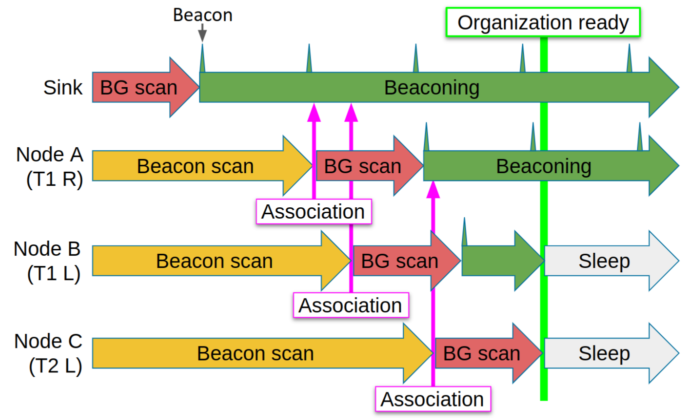

Fig. 1 A diagram of a simple network initial organization process of where tier 1 (T1) node A becomes a router (R) and T1 node B and tier 2 (T2) node C become leaf nodes (L).

After a PT has successfully associated itself with an FT, the PT switches to FT mode and performs FT mode operations, i.e. BG scanning and beaconing, in order to advertise itself as a potential parent to its nearby nodes and by that extend the coverage area of the network to a new tier of nodes. The nodes associated directly to the sink form tier 1, the nodes associated with tier 1 nodes form tier 2 nodes, etc.

As this organization cycle continues from tier to tier, the mesh network size can theoretically increase to extreme distances. The cycle continues until all nodes within a certain coverage area are associated with another node. In the simulations we let all the nodes perform BG scanning after their association and after all nodes have performed it, we consider the initial organization phase finished and the network complete, after which all nodes initiate traffic transmissions.

Some nodes in the network are left as pure PT nodes, i.e. leaf nodes. These nodes cancel their advertisement beaconing after organization is finished and go to sleep, only to wake up listening to their parent's beacon or to transmit data.

III. NETWORK ROTATION PROCESS

In this section we explain how the DECT-2020 NR network rotation is executed in this study. It should be noted that the purpose of this paper is to describe the basic principles of the rotation process and focus on the actual impact of it to the network performance. Thus, we address the implications and the mere feasibility of implementing the process in a real network only superficially in this paper.

A diagram of a rotation process in a simple network is depicted in Fig. 2. The protocol consists of the following phases: association release, advertisement and reassociation, which are explained in the following sections.

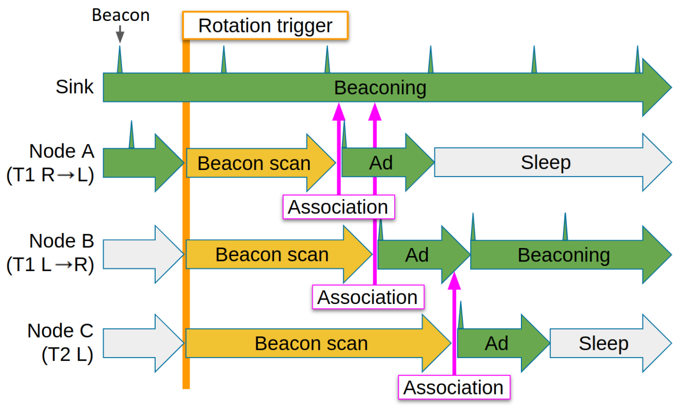

Fig. 2 A diagram of a rotation process in a simple network, where tier 1 (T1) node A switches its role from router (R) to leaf (L) and node B vice versa.

A. Association release phase

Rotation is always triggered by the sink, which starts an association release phase. The sink releases the associations to its children by transmitting an Association Release message to each of them. The release process then continues recursively so that a node receiving an Association Release message from its parent will forward the message also to its own children, if such exist. Hence, the process continues down on all the branches of the mesh network recursively until all associations in the network are released and all nodes are left orphans.

It is to be noted that during the association release phase, traffic generation still persists in every node, so the association release causes an inevitable service interruption. Thus, the periodicity of triggering the rotation should be selected so that the interruption time is minimized whilst making sure that as many nodes as possible get a chance to act as a router before the first ones deplete their batteries. However, any reasonable IoT use case assuming battery-operated nodes needs to have a relatively low traffic intensity in order to ensure an adequate node lifetime [8]. Low traffic intensity means a packet interval of e.g. several hours per node and results in years of expected router battery life while the service interruption due to rotation is likely to be over in minutes, depending on the beacon interval and the depth of the cluster tree network. Thus the rotation occurring e.g. once per day is likely short enough to allow the network to go through all possible router constellations many times during the network lifetime. A rotation interval sparse as this most likely has a negligible effect on the service quality.

B. Advertisement phase

Upon becoming an orphan after the association release phase, a node starts beacon scanning immediately to find a new parent. In order to ensure that the roles of the network nodes are truly rotated, all nodes who associate need to send an advertisement in order to establish as many reassociation opportunities as possible for the remaining orphans.

Upon associating with an FT, a PT node becomes an advertising FT (AFT) where it temporarily sends beacons and enables its RACH listening. Nearby orphans in beacon scanning mode thus have an opportunity to hear the AFT and associate with it. If AFT receives association requests during its advertisement phase, it becomes a router and continues beaconing. Otherwise it switches back to PT mode after the advertisement phase and continues as a leaf node until the next rotation. The duration of the advertisement phase is a network parameter. In our simulations, we assumed one beacon period duration for this. A longer advertisement phase would increase the success rate of associations with AFT, but also its energy consumption.

Contrary to operation during the initial organization phase, AFTs do not perform BG scanning before starting the advertisement beaconing. It is assumed that the channel selection made during the initial organization phase remains valid as almost all nodes transmitted beacons during it and were therefore able to be heard and avoided by their neighbors. A small risk of mutual interference between neighbors after reassociation is always left, but in this study we calculated the benefit of energy saving by not performing a new BG scan after each reassociation greater than the risk of potential interference.

C. Reassociation phase

The phase with the most impact on the rotation process is the reassociation phase. Here the PTs select new parents after they have received one or multiple cluster beacons.

An intuitive value to base the FT selection on would be the received beacon signal strength. If PTs prioritize the candidate FTs who transmitted the strongest beacons, it would presumably minimize the error probability and the required Tx power of transmissions between them. This would obviously impact positively on the battery life in that sense. However, assuming the positions of the nodes in the network do not change, basing the selection on beacon signal strength would mean that the nodes would always select the same routers as parents, whenever there was an attempt to reorganize the network. This would cement the roles in the network and effectively eliminate the possibility of rotation.

Generally, in order to achieve rotation of roles in the network, the FT selection should be made based on a metric which is not fixed throughout the lifetime of the network. In order to achieve as even energy consumption among the nodes as possible, we propose that the FT selection should prioritize associations to FTs with the highest battery level. This way after the rotation, nodes with low battery level would be more likely to end up in leaf role, in which they can save energy and stay connected to the network longer.

Router battery state is not specifically embedded into the cluster beacon message in current DECT-2020 NR specifications. However, implementations using the current specifications could base their reported route cost metric value to the inverse of their battery level and this would have the same effect. Another option would be to introduce a new battery level IE to the beacon message which then could be utilized by the PT nodes in FT selection along with the route cost metric.

IV. Simulations

For this study we used an open-source Network Simulator 3 platform [11] into which we implemented a module for DECT-2020 NR. The module consists of the MAC and PHY layers implemented according to ETSI TS 103 636 series specifications [1]. The details of the simulator modeling are explained in [8]. We added the periodic rotation process explained in section III and modified the FT selection process of the simulator accordingly.

TABLE I. Simulation parameters

Parameter	Value
Scenario radius	800 m - 5 km
Frequency	1.89 GHz
DECT channels	10
Propagation model	ITU Urban Macro
Shadowing	Disabled
Channel model	5G spatial channel model [13]
Number of nodes	[1000, 3000, 5000]
Number of sinks	1
No of simulation drops per case	20
Simulation duration	24 h
Antenna model	1x1 omni, 0 dBi gain
Noise figure	7 dB
Beacon Tx power	23 dBm
Minimum beacon quality for association	3 dB
Route cost	Inverse of FT battery level
Power control	Pathloss based: TxP [dBm] = min (23, -68 - 0.7 * path gain)
Max HARQ retransmissions	9
HARQ processes per node	2
SCS scaling factor	1
FFT scaling factor	1
LBT min CW	8
LBT max CW	64

Table I shows the general simulation parameters and assumptions. We simulated a DECT-2020 NR network in an IoT scenario consisting of different amounts of nodes, from 1000 to 5000, to cover different network loads. Nodes were randomly positioned in each simulation drop. The centermost node was selected as the sink in each drop. Scenario radius was also varied in order to capture the effects of different sized mesh topologies with different amounts of routers and tiers.

As found in [8], a battery-operated DECT-2020 NR mesh network is reasonable only with low traffic intensity and relatively loose delay requirements. A high traffic intensity severely decreases the network lifetime (resulting in mere days of operation time), to which no energy saving mechanism is able to do much about. Thus, in the simulations, we assumed a general battery-operated IoT sensor network use case with relatively low traffic intensity and set the parameters to minimize node energy consumption whilst still ensuring adequate service. The details of the selected use case and its traffic parameterization are shown in Table II.

In the result analysis, we focused on the impact of router rotation to the node battery life expectation and to system performance in terms of end-to-end packet delay and the service rate, which is the percentage of the transmitted data that is successfully received by the target node (the sink). End-to-end delay was measured from the time a packet was generated in the source node to the time when it was successfully received at the target node.

Each node transmits a packet to the sink once per 24 hours. The rotation period was set to 2 hours, a short period in relation to expected node lifetime, to ensure some rotations occur during the 24 h simulation time. During the rotation period, the network as a whole relays on average 83-417 packets through (depending on the number of nodes) and, with a beacon interval of 32 seconds, each router transmits 225 beacons and listens to as many RACH occasions.

TABLE II. Simulation use case

Parameter	Value
Real-life use case examples	Smart energy demand response management (DRM), Smart transport road condition monitoring, Smart agriculture irrigation / fertilization / pest control [12]
Tolerable delay	Few minutes
Beacon interval	32 s
Router RACH period	1 x 20 ms per beacon period
Traffic	100 B data packet / 24 h / node
Rotation triggering period	2 hours
Traffic direction	Unidirectional, targeting sink

Table III shows the used energy parameters. Expected node battery life for each node was calculated from their experienced energy consumption during the simulation, which was defined by the electric current usage of the radio states they were in. State transitions did not consume any additional energy. The used currents in different radio states were based on actual values of an existing Nordic Semiconductor nRF9160 LTE-M/NB-IoT modem [13] and thus they are expected to reflect the values of an upcoming DECT-2020 NR modem also.

TABLE III. Energy parameters

Parameter	Value
Battery capacity	18 kJ (5 Wh)
Voltage	3.7 V
Sleep state current	8 μA [15]
Rx/LBT state current	45 mA [15]
Tx state current	Linear Tx current = TxP (W) / (3.7 V * 0.37) + 0.045 A [14]

The energy consumption of the nodes was collected only after the initial network organization phase, so the increased energy consumption of nodes due to additional beaconing and RACH listening during the advertisement phase of the rotation process was accounted for in the expected node lifetimes.

In the analysis, we assume minimum node battery life as the metric to reflect the performance of the router rotation protocol. Minimum node battery life is the shortest experienced lifetime of a node in the network in the simulations i.e. the maximum time all nodes are still in the network, which is the desired situation. The longer the minimum node battery life, the longer the network is intact and the better is the performance of the rotation protocol.

V. Simulation results

Fig. 3 shows examples of simulated network topologies of 1000 nodes with some selected scenario radiuses. Different network tiers are depicted with a different color. The figure demonstrates how the network has only few tiers when nodes are within a small radius, but as the nodes are dispersed over a larger area, the network requires more tiers to cover the whole scenario.

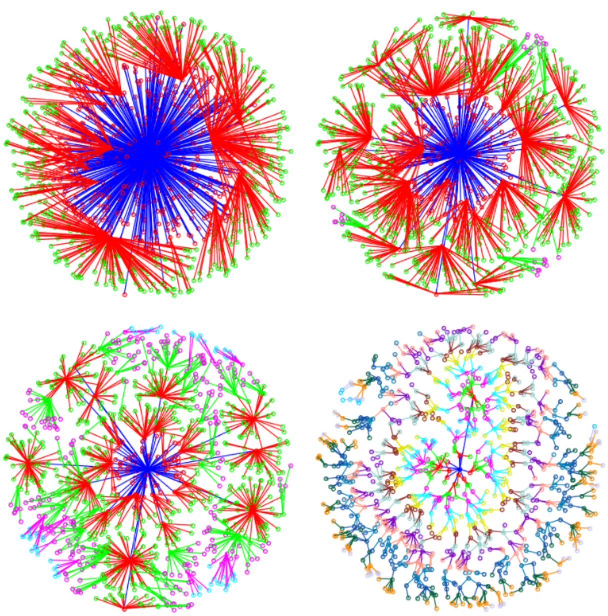

Fig. 3 Examples of simulated 1000 node network topologies with 800 m (top left), 1200 m (top right), 2000 m (bottom left) and 5000 m (bottom right) scenario radiuses.

Fig. 4 shows the minimum node battery life with different user loads and scenario radiuses. With the given duty cycle assumptions, without rotation, the first node dies after 0.1-1.5 years of network uptime, on average, depending on the load and the mesh network radius.

With rotation, the average minimum lifetime is increased threefold in smaller scenarios and low network load. The rotation battery life gain increases as the load increases from 1000 to 3000 nodes but diminishes with a higher load. The increase is likely caused by the increased number of candidate routers: with a larger node pool to pick a new router from, individual nodes can avoid the routing responsibility much longer, prolonging their lifetimes.

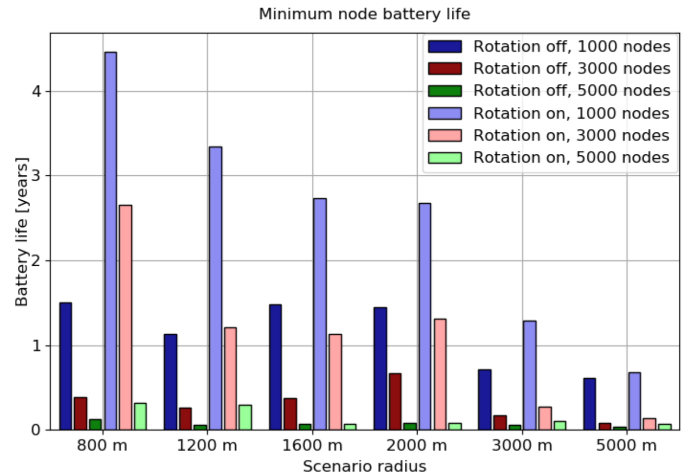

Fig. 4 Minimum node battery life with different scenario radiuses and user loads.

In absolute terms, router lifetimes decrease as more nodes are introduced to the network due to increased traffic and consequently increased activity in router nodes.

In larger scenarios the battery life gain from rotation is smaller than with smaller scenarios. With larger radius the network is spread thinner and there are less candidates near router nodes to replace them. Thus the rotation responsibility is rotated between fewer nodes and some nodes may even be irreplaceable as routers, which decreases the overall achievable gain in battery life.

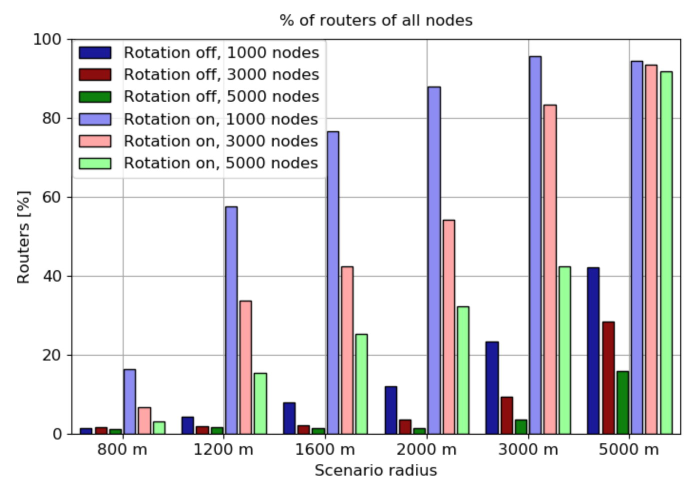

Fig. 5 Percentage of nodes participating in traffic routing during simulation with different scenario radiuses and user loads.

Fig. 5 shows the percentage of nodes who participate in traffic routing at any given time during the simulations on average. Without rotation, only a small percentage of nodes act as routers in small scenarios. This is because in a small geographical area, all the nodes can be covered easily with only a few routers. In larger scenarios more nodes need to participate in routing to achieve full coverage. Without rotation, with the largest scenario radius, 20-40 % of network nodes act as routers, which naturally limits the possibilities to rotate their roles.

Fig. 6 shows the achieved end-to-end delays in different cases. The delays are relatively long, measured in minutes in all cases, but all being within accepted delay tolerance of the use case. When comparing the results with and without rotation, we see that rotation has a minimal effect on the experienced delays. This is as expected since the rotation interval is long in relation to the traffic generation interval.

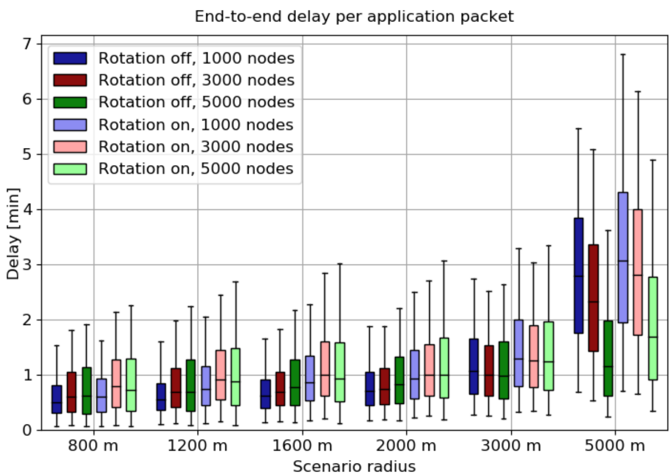

Fig. 6 Box plots showing 5th, 25th, 50th, 75th and 95th percentile of end-to-end delay with different scenario radiuses and user loads.

Also from Fig. 7, showing network service rate, we can see that increasing user load significantly degrades service rate due to data building up in the routers. Battery life is consequently decreased due to increased activity from retransmissions.

Rotation on the other hand degrades service rate so slightly that if application QoS requirements demand it, the degradation can most likely be counteracted with a minimal RACH duration increase, which presumably would not decrease the router lifetimes as much as the rotation would increase it.

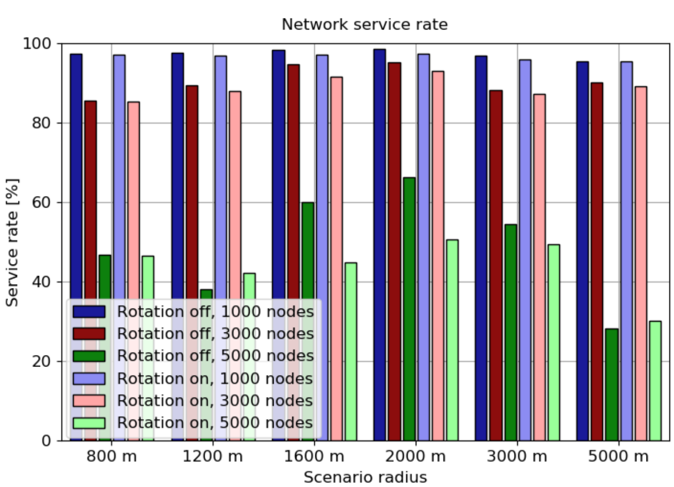

Fig. 7 Network service rate with different scenario radiuses and user loads.

VI. Conclusions

In this paper we showed that a periodic router rotation is able to balance the energy consumption of DECT-2020 NR mesh network nodes more evenly and thus significantly increase the lifetime of a battery-operated IoT sensor network without degrading the network performance, such as traffic delay and network service rate. The gain in node router lifetime is inversely proportional to mesh network size in terms of both geographical area and number of nodes.

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