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MAC Enhancements for G3-PLC Home Networks

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***Abstract*—In this paper, we propose enhancements at the medium access control (MAC) sub-layer for the G3-PLC technology. In particular, we develop a convergent network, consisting of different network devices, to easily integrate G3-PLC in Ethernet local area networks (LANs). The proposed network leads to coverage and throughput improvements for in-home/building applications. Furthermore, since the G3-PLC medium access control (MAC) scheme is based on carrier sense multiple access (CSMA), its performance decreases with the increasing number of network nodes. To overcome this problem, we propose to implement a contention-free MAC scheme based on time division multiple access (TDMA). In particular, we optimize the beacon-enabled mode of the IEEE 802.15.4 standard. The convergent network performance is evaluated using an OMNeT++ simulation platform. Numerical results show considerable performance improvements in different network configurations.**

I. Introduction

In the near future, the power grid needs to become a distributed large scale system that has to smartly manage flows of electricity produced by big or small plants, i.e., a smart grid (SG). Demand side and demand response mechanisms have to be implemented, so that consumers and producers will actively collaborate in the use and delivery of energy [1], [2].

In this perspective, an important role is played by the communication technologies, which can enable, the smart home concept, i.e., the penetration of the SG within the home/building context, by means of smart management and monitoring of household appliances, control of local renewable energy plants (e.g., photovoltaic generators), monitoring of electric vehicles charge, etc..

Industries and standardization organizations have proposed the use of narrow band (NB) power line communication (PLC) technologies to support the development of the SG concept. Several solutions and standard have been developed with this aim, e.g., the PRIME [3] and the G3-PLC [4] technologies for smart metering applications, the new IEEE P1901.2 and ITU-T Ghnem standard for SG applications [5]. However, we highlight that so far, only PRIME and G3-PLC solutions have been largely used, and in particular, for automatic meter reading (AMR).

In this paper, we consider the G3-PLC solution, for which we propose enhancements at the medium access control (MAC) sub-layer to allow the implementation of SG applications that could potentially require higher data rate than AMR.

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The choice of considering the G3-PLC solution is motivated by the two following reasons. Firstly, it has been used as baseline technology for the development of the IEEE P1901.2 and ITU-T G.hnem standard [5]. Secondly, through field trial tests, we found that the performance of NB-PLC may be poor [6] in large houses where the signal is strongly attenuated because it spans large distances and crosses different circuit breakers (CBs), e.g., in multi-floor houses.

The first enhancement that we propose is a convergent network consisting of different network devices, i.e., *end nodes*, *routers* and *switches*, to integrate G3-PLC with Ethernet devices. This, in turn, leads to an increased network coverage and improves the network throughput.

The second enhancement that we propose is the adoption of a contention-free MAC scheme based on time division multiple access (TDMA), instead of the carrier sense multiple access with collision avoidance (CSMA/CA) scheme specified by G3-PLC. In particular, we implement an optimized version of the beacon-enabled mode of the IEEE 802.15.4 standard [7]. The reason behind the use of a TDMA scheme is that the performance of CSMA/CA decreases with an increasing number of network nodes.

The convergent network performance together with the TDMA scheme are evaluated through the implementation in the OMNeT++ network simulator [8]. Numerical results show considerable performance improvements in different network configurations.

The remainder of the paper is as follows. In Section II, we summarize the main characteristics of the PHY layer and MAC sub-layer of the G3-PLC technology. Then, in Section III, we describe the convergent network and its main devices. In Section IV, we discuss the implementation in OMNET++ of the convergent network and we provide first simulation results. The TDMA optimization is presented in Section V together with extensive simulation results. Finally, in Section VI, we draw the conclusions.

II. G3-PLC Technology

According to [4], the G3-PLC technology has been designed to support CENELEC, ARIB and FCC bands in the frequencies range between 10 kHz and 490 kHz. It makes use of pulse shaped - orthogonal frequency division multiplexing (PS-OFDM) carrying DQPSK, or DBPSK symbols in "normal" or "robust" mode. The correspondent maximum data packet is 235 (DQPSK), 235 (DBPSK "normal") and 133

Fig. 1. G3-PLC PHY frame format.

(DBPSK "robust") bytes. The maximum achievable bit-rate is 33.4 $kbps$ using DQPSK.

The PHY frame format (see Fig. 1) is characterized by (i) the preamble, which is a multi symbol field used to perform carrier sense operations, to enable control functions and to synchronize the receiver and the transmitter, (ii) the frame control header (FCH), which carries control information required to correctly demodulate the received signal, (iii) the data payload. The data payload length (n) depends on the transmission mode, i.e., normal and robust. In normal mode, the forward error correction (FEC) is performed through a Reed Solomon (RS) encoder and a convolutional encoder, whereas the error check is done with a frame check sequence (FCS). In robust mode, beside RS and convolutional encoding, there is a repetition code (RC) that repeats each bit following the preamble 4 times.

When showing simulation results, we consider G3-PLC working in the CENELEC-A band. In this case, it uses PS-OFDM with raised cosine window, and $M = 256$ sub-channels out of which $N_c = 36$ are used in the 35.9-90.6 kHz frequency band. Furthermore, we assume the PHY frame to last $N_s = 40$ OFDM symbols that carry data modulated with DQPSK. This assumption leads to $n = 163$ bytes of data with 16 bytes of RS parity. Consequently, the maximum achievable bit-rate is 29.6 $kbps$. We also assume that the transmission does not wait for any acknowledgement (ACK). Table I reports the set of the PHY layer parameters.

TABLE I
G3-PLC SYSTEM SPECIFICATIONS.

Number of PS-OFDM symbols	$N_s = 40$
Number of IFFT/FFT points	$M = 256$
Number of used sub-channels	$N_c = 36$
Number of overlapped samples	$N_o = 8$
Number of cyclic prefix samples	$N_{CP} = 30$
Number of FCH symbols	$N_{FCH} = 13$
Sampling frequency [MHz]	$f_s = 0.4$
Number of preamble symbols (without FCH)	$N_{pre} = 9.5$

According to [9], the G3-PLC MAC sub-layer is based on the IEEE 802.15.4–2006 specification for low-rate wireless personal area networks (WPANs) [7]. Basically, the channel access method is based on carrier sense multiple access with collision avoidance (CSMA/CA) mechanism and a random backoff time.

III. Convergent Network Implementation

Our challenge is represented by the integration of G3-PLC technology into an Ethernet network. Since the switched Ethernet network exhibits a star topology and the power line channel can be considered as a bus, we adopt a tree like topology – as a combination of bus and star topologies – to implement the convergent network (see Fig. 2). The major benefit deriving from the use of such a topology is its ability to be scalable, extensible, and reliable. The convergence between Ethernet and G3-PLC can be obtained through the definition of a shared common layer that provides interconnectivity among heterogeneous lower layers.

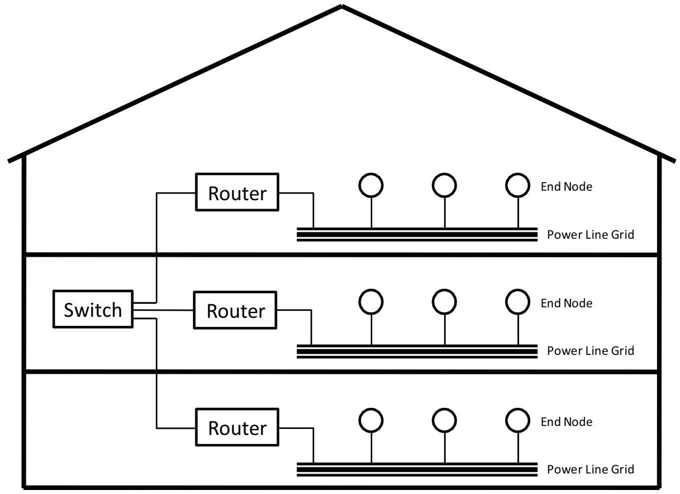

Fig. 2. Network topology.

The network convergence is achieved by defining different network devices, i.e., *end nodes*, *routers* and *switches*.

A. End Nodes

They represent the devices of the network that directly interact with the surrounding environment, e.g., sensors, actuators, switches, meters and so on. These nodes are grouped into subnetworks according to the same communication technology, i.e., G3-PLC. From a logical point of view, the end nodes can be all characterized by the same building blocks, i.e., a traffic generator – which is responsible of data packets generation –, and the network adapter. The network adapter comprises a PHY, a MAC, and a buffer of data packets coming from the traffic generator.

B. Router

Since G3-PLC does not provide any specification for the integration in switched Ethernet network, we need a network device that groups G3-PLC nodes into a subnetwork and integrates the subnetwork with the rest of the Ethernet network. To do that, we define a router that offers network adapters towards both Ethernet and G3-PLC. Beside the network adapters, the Router has a routing module that is responsible of translating and forwarding packets from one network adapter to the other and vice versa: this module is responsible of interconnectivity between Ethernet and G3-PLC. As depicted in Fig. 3, the routing module keeps trace of packets received from its subnetwork nodes, and it generates a forwarding table with *source address*, *insertion time*, and *link quality*. In this perspective, the router dynamically learns about the existence of nodes during reception of packets and modifies its table updating the link quality or removing aged entries, according to the insertion time. It is worth noting that a given subnetwork can

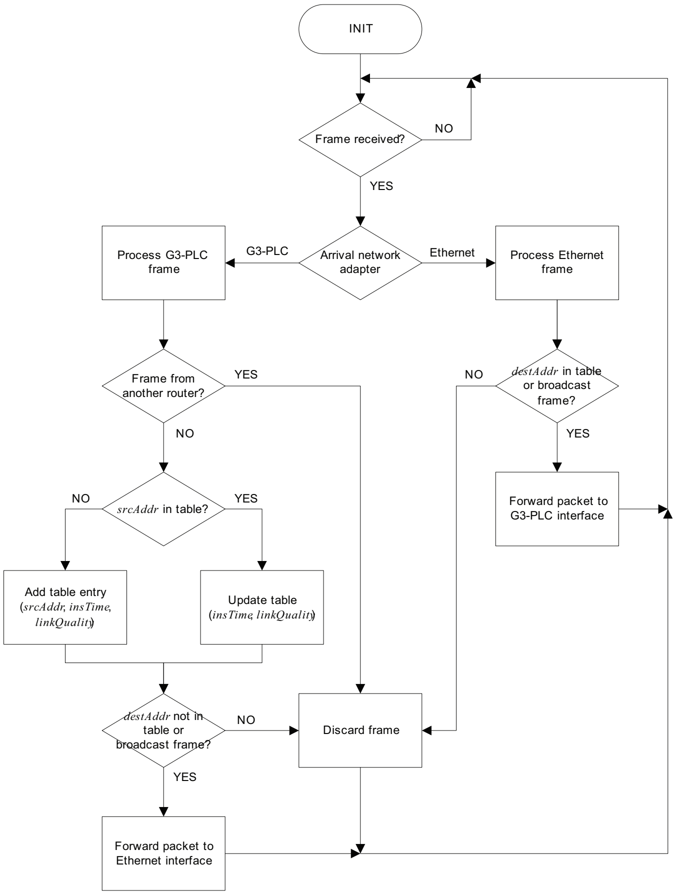

Fig. 3. Router flow chart.

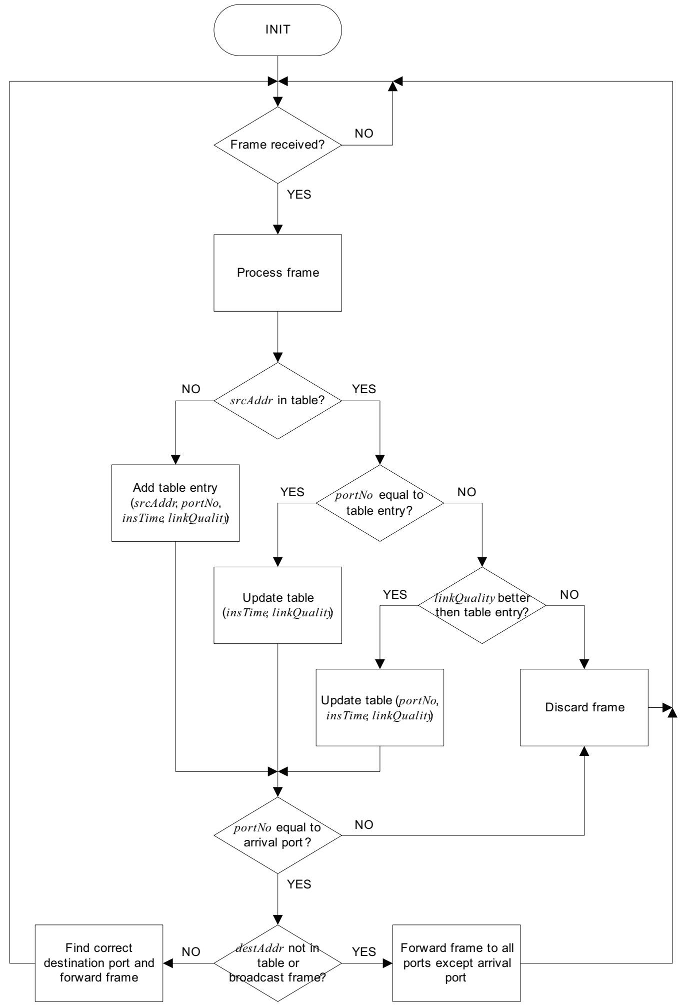

Fig. 4. Switch flow chart.

be managed by two (or more) routers in order to ensure a more reliable communication on harsh power line channels, or equally, to increase the network coverage. Furthermore, in order to prevent loops, the router is able to recognize and discard packets directly arrived from other routers.

C. Switch

The switch is a well-known network device, especially in today's networks. As depicted in Fig. 4, the switch has been modified in order to work seamlessly with the routers. In particular, it is able to build and update a forwarding table exploiting nodes information harvested by each router. A forwarding table entry is composed by *source address*, *insertion time*, *link quality* and arrival *port number*. Therefore, the switch compares the information carried by a packet with the correspondent table entries and forwards the packet to the correct port (or broadcast if the destination address has no correspondence in the table). In this case, the insertion time parameter is exploited to remove aged entries from the table and thus increasing the system fault tolerance. Again, the switch is able to prevent packet loops. We also point out that since link quality is updated periodically, the switch is able to dynamically handle the network changes. It is now clear that the combination of the router and switch procedures allows for integrating heterogeneous communication technologies leading to a convergent network. Moreover, this combination provides the basis for satisfying quality of service (QoS) constraints.

It should be finally noted that the integration of the G3-PLC with Ethernet easily allows for integrating the G3-PLC technology in IP networks.

IV. OMNET++ Implementation and Results

Starting from the communication technologies, we have implemented the PHY layer and the MAC sub-layer of (i) G3-PLC according to the details previously described, and (ii) Fast Ethernet over twisted pair cables, i.e., 100BASE-TX. To this aim we have used the OMNeT++ network simulator and its extension INET-Framework [10]. OMNet++ is an open source, component-based simulation library and framework that is primarily thought for building network simulators. Basic components, i.e., *simple modules*, are programmed in C++ and then combined into larger components, i.e., *compound modules*, using a network description (NED) language. NED language is also used to connect compound modules and assemble the whole network.

In order to quantify the convergent network performance, we define a representative metric, namely, the aggregate network throughput (THR). It is evaluated as

$$THR = \sum_{u=1}^{N} THR^{(u)} \quad [bps]\,, \tag{1}$$

where N is the number of network nodes and $THR^{(u)}$ is the average throughput achieved by the u-th node, which is obtained as

$$THR^{(u)} = 8nN_g^{(u)} \quad [bps]\,, \tag{2}$$

where n are the data bytes encapsulated in the PHY frame, $N_g^{(u)}$ is the number of correct received PHY frames per second by the u-th node.

In order to model the transmission channel in OMNET++, we make use of the results presented in [6] that were obtained from a trial campaign. According to the obtained results, we model the packet error rate (PER) of each power line channel as a uniformly distributed random variable. In detail, we assume $PER^{(u)} \sim \mathcal{U}(0,\ 0.056)$ and $PER^{(u)} \sim \mathcal{U}(0,\ 1)$, respectively for best and worst case. The best case is representative of houses that are fed by a single circuit breaker (CB), e.g., single floor houses. Whereas, the worst case is representative of houses where the signal crosses different CBs, i.e., multi-floor houses where each floor is fed by a given CB. Regarding the Ethernet channels, according to [11], we assume cat5 cables with bit error rate (BER) equal to 10^{-10} (worst case).

We build the simulation scenario using from 6 up to 60 G3-PLC nodes and we evaluate the THR without routers, or when two and three routers – e.g., one per each floor, – are considered. The traffic is generated in order to reach saturation conditions, i.e., the limit reached by the THR when the offered load increases, and it represents the maximum load that the system can carry [12]. In these conditions, each node has immediately a packet available for transmission, after the completion of each successful transmission. Furthermore, the traffic destination is randomly chosen among the G3-PLC nodes belonging to the same subnetwork or to different subnetworks, when routers are present. As we can see in Fig. 5, the introduction of 2 and 3 routers substantially improves the performance. It is worth noting that the THR improvements directly translate into a coverage extension.

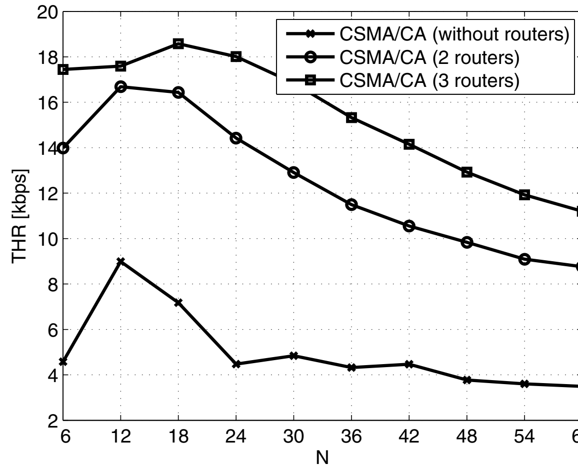

Fig. 5. Aggregate throughput according to different network configurations using CSMA/CA.

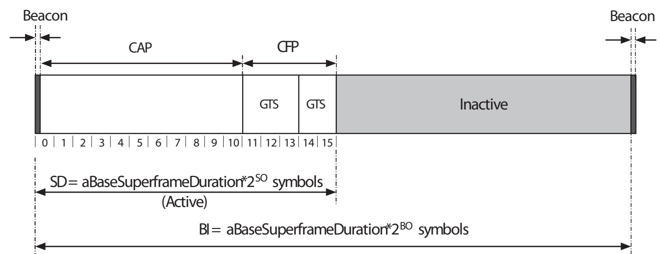

Fig. 6. An example of superframe structure for the beacon-enabled mode of the IEEE 802.15.4.

V. G3-PLC ENAHNCEMENTS

Despite the THR improvements related to the introduction of routers, the bottleneck of the network is represented by the degradation of the performance with the increasing number of G3-PLC nodes within each subnetwork (see Fig. 5). To limit the degradation, we propose a different channel access method that provides higher QoS, namely, time division multiple access (TDMA). To do this, we implement the *beacon-enabled* mode of the IEEE 802.15.4–2006 specifications [7]. It makes use of a *superframe* structure as depicted in Fig. 6. Each superframe is defined by the beacon order (BO), it lasts $BI = aBaseSuperframeDuration * 2^{BO}$ OFDM symbols, and it is characterized by an active and an inactive part. The active part, which is defined by the superframe order (SO), lasts $SD = aBaseSuperframeDuration * 2^{SO}$ OFDM symbols, and it consists of a contention access period (CAP) and a contention-free period (CFP). The BO, and the SO values are related according to $0 \leqslant SO \leqslant BO \leqslant 14$. In the CAP, the channel access is based on CSMA/CA, while during the CFP, it is based on TDMA. The active portion of each superframe is divided into a number of time slots equally spaced, whose duration is given by $aBaseSlotDuration = N_s + aInterFrameSpacing$, where N_s is the number of OFDM symbols in a G3-PLC frame (see Table I), and $aInterFrameSpacing$ is the interframe space within two time slots. The CFP grows or shrinks dinamically fulfilling the minimum CAP length of 440 OFDM symbols. We denote with N_{TStot} the number of time slots present in the CFP.

It is worth noting that the beacon frame, which is periodically sent by a WPAN coordinator for synchronization purposes, can be replaced by the synchronization with the mains cycle.

Table II reports the values of the parameters used for the beacon-enabled mode simulations.

Now, in order to maximize the aggregate network rate, each subnetwork coordinator, represented by a router, assigns a guaranteed time slot (GTS) – which lasts one or more time

TABLE II
SUPERFRAME PARAMETERS AND VALUES.

Parameters	Value
$SO = BO$	$1,\ 2,\ 5$
$aBaseSuperframeDuration$	$aBaseSlotDuration*$ $aNumSuperframeSlots$
$aBaseSlotDuration$	$N_s + aInterFrameSpacing$
$aInterFrameSpacing$	10
$aNumSuperframeSlots$	16

slots, – to each node that wants to transmit, by solving the following optimization problem

$$\max_{\underline{N}_{TS}} \sum_{u=1}^{N} \frac{N_{TS}^{(u)}}{N_{TStot}} THR^{(u)}$$
$$s.t. \sum_{u=1}^{N} \frac{N_{TS}^{(u)}}{N_{TStot}} = 1, \quad (3)$$
$$\frac{N_{TS}^{(u)}}{N_{TStot}} THR^{(u)} \geq p^{(u)} THR^{(u)} \quad \forall u = 1, \ldots, N,$$

where N is the number of nodes, $N_{TS}^{(u)}$ is the number of time slots assigned to node u, and $\underline{N}_{TS} = \left[N_{TS}^{(1)}, N_{TS}^{(2)}, \ldots, N_{TS}^{(N)}\right]$. Furthermore, $THR^{(u)}$ is the throughput of node u in bps. It can be obtained as $THR^{(u)} = 8n(1 - PER^{(u)})/T_s$, with T_s denoting the time slot duration in seconds. $p^{(u)} \in [0, 1]$ are QoS coefficients, each indicates the percentage of the throughput that the u-th node has to achieve w.r.t. the one that it would achieve in the corresponding single user scenario. Finally, the condition in the second line of (3) forces all the time slots in a CFP to be used.

Problem (3) is an integer linear programming problem. Therefore, it is, in general, NP hard. To simplify the problem, we solve (3) using linear programming (LP) and we round the obtained coefficients to the lower closest integer value. Clearly, there could be cases where the number of slots assigned to one or more nodes is zero. In these cases, the correspondent nodes are deferred to transmit in the CAP. Furthermore, when some time slots are not occupied as result of the rounding of the coefficients, these will be assigned to the nodes that have the highest throughput, leaving the CAP free of transmissions. Finally, we assume $\sum_{u=1}^{N} p^{(u)} \leq 1$. The latter assures that the LP always give a feasible solution if $N \leq N_{TStot}$.

It is easy to prove that when $\sum_{u=1}^{N} p^{(u)} = 1$, e.g., $p^{(u)} = 1/N$, the optimal solution to (3) can be found imposing the Karush Kuhn Tucker (KKT) conditions [13] and is given by $N_{TS}^{(u)} = N_{TStot}/N \ \forall \ \ u = 1, \ldots, N$. In the following, we assume the last condition holds true.

Now, in Fig. 7, we show the aggregate network throughput, when no router is present, obtained using CSMA/CA and the proposed TDMA with $PER^{(u)} \sim \mathcal{U}(0,\ 1)$ (top) and $PER^{(u)} \sim \mathcal{U}(0,\ 0.056)$ (bottom). The results are shown for $SO = \{1,\ 2,\ 5\}$, namely for superframe duration of $\{1.72,\ 3.43,\ 27.47\}\ s$, or equally for a number of slots in the CFP equal to $\{23,\ 55,\ 503\}$. We notice that we have not found any substantial improvement for value of SO greater than 5.

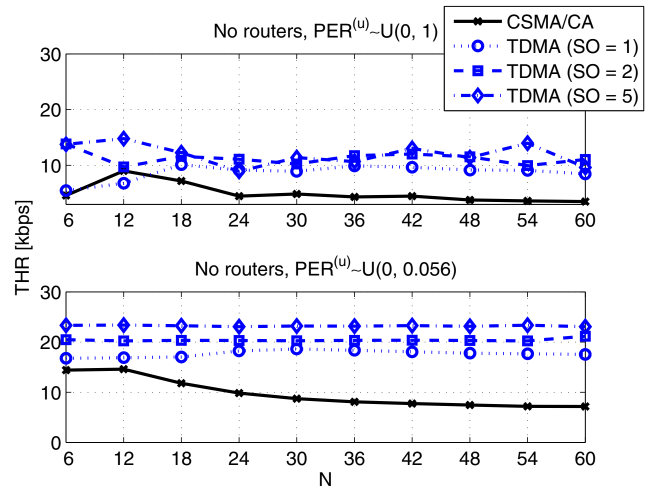

Fig. 7. Aggregate throughput comparison between CSMA/CA and TDMA for a network configuration without routers.

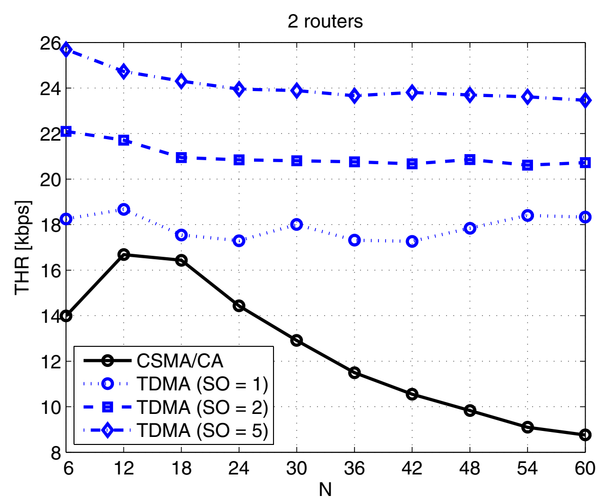

Fig. 8. Aggregate throughput comparison between CSMA/CA and TDMA for a network configuration with 2 routers.

Fig. 8 and Fig. 9 show the comparison between TDMA and CSMA/CA when 2 and 3 routers are used. It is assumed $PER^{(u)} \sim \mathcal{U}(0,\ 0.056)$.

From Figs. 7, 8, 9 we derive the following observation.

- In general, the TDMA scheme allows a substantial increase of the aggregate network throughput w.r.t. CSMA, even when SO is equal to 1.
- The use of TDMA solves the bottleneck problem of CSMA represented by the considerable degradation of the performance with the increasing number of nodes within each subnetwork.
- The minimum CAP length constraint, specified by the 802.15.4 standard, affects the behavior of the aggregate throughput in two ways. Firstly, there is an improvement of the throughput increasing the number of time slots (namely SO). This is because, in many cases the largest

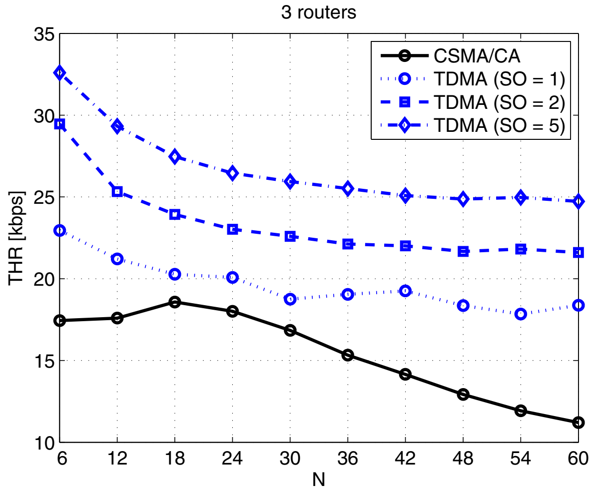

Fig. 9. Aggregate throughput comparison between CSMA/CA and TDMA for a network configuration with 3 routers.

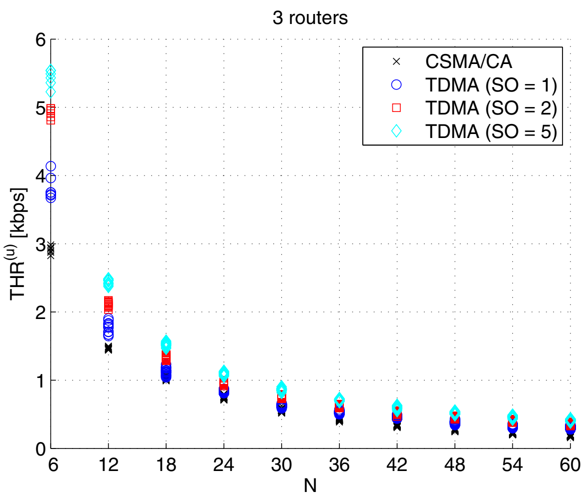

Fig. 10. Throughput achieved by each node in a 3 routers network using CSMA/CA or TDMA.

part of the CAP is not used and thus by increasing the duration of the super frame, the impact of the CAP on the throughput decreases. Secondly, the throughput exhibits a faster decay when considering 2 and 3 routers w.r.t. the no router case. This is because the negative effect of the CAP is present in each sub-network, namely twice or three times, respectively.

- The aggregate network rate increases by increasing the number of routers. This is because the same resources are shared within each subnetwork by a smaller number of nodes.

We now focus on the throughtput achieved by the single network nodes. Fig. 10 shows the throughput achieved by each network node when three routers are deployed (see Fig. 9). From Fig. 10, we note the following.

- The throughput achieved by each network node with TDMA is always higher than that of CSMA.
- CSMA appears more fair than the considered contention-free approach. In fact, in TDMA, the variance of $THR^{(u)}$ is higher than in CSMA.

VI. Conclusion

The performance of G3-PLC can be substantially improved in-home/building scenarios by enhancing its MAC sub-layer. In particular, a convergent network architecture that allows the integration of G3-PLC with Ethernet can be adopted (a) to cope with the strong channel attenuation that is present in houses/buildings where the signal crosses circuit breakers, and (b) to increase the available resources by splitting the nework in sub-networks. Although the convergent network leads to a substantial increase of the aggregate network throughput, its performance appreciably decrease with the increase of the number of network nodes. This is mainly due to the use of the CSMA/CA MAC scheme of G3-PLC. A contention free MAC scheme based on an optimized version of the beacon-enable mode of the IEEE 802.15.4 can be implemented to solve this problem and further increase the aggregate network throughput.

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