Relay-aided Networking for Power Line Communications

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***Abstract*—We consider a smart grid Power Line Communications Network (PLCN) which serves stations that represent subscriber devices or sensor stations. The network is managed by a control (gateway) station that is attached to a power line and acts to supervise and control the sharing of the PLCN medium by stations attached to the line. We design a networking mechanism that enables active stations to efficiently transport their message flows to the gateway. Our approach is based on the selection of certain stations to act as relay stations, forming a forwarding backbone. Relay stations are directed to adapt their code rates and scheduling mechanism in aiming to achieve high spatial reuse levels that induce high throughput rates.**

I. Introduction

The design of a smart grid [1] is enabled by the use of environmentally aware intelligent devices to configure the system to provide efficient and robust services for power distribution. To facilitate this operation, it is essential for the control and management system to gain timely and robust access to the state of of the system (including utilizations states at energy consuming and producing entities) and then upon reconfiguration, disseminate in a robust and timely manner control data to regulated entities. For this purpose, it is essential that the services of an available, responsive and high capacity network system are embedded within the smart grid infrastructure. In considering the application of smart grid technology to regulation of energy resources used in the home, a communications network system is provided for connecting home appliances, sensors, energy use metering devices, and security oriented entities to a gateway station that interfaces the smart grid infrastructure. Using this home network, the smart grid system can provide services that support coordination among indoor appliances or sensors, and transport safety message flows that are produced by exception events, such as a multitude of security alarms.

To facilitate the implementation of such home networks in a cost effective manner, it is of interest to make use of deployed power line systems. A Power Line Communications (PLC) system [2] is thus employed to communicate message flows that are generated at times by home based devices. The latter stations are attached to the power line, and use the PLC system to communicate its messages and receive control commands in return to an attached gateway station/control station. By properly designing the PLC system, it is possible to alleviate the occurrence of severe indoor shadowing effects that characterize the deployment of a wireless network system. For this purpose, several standards, including HomePlug AV [3] and IEEE 1901 [4], have been established. They aim to use the instituted PLC home network to not only carry control message flows but also provide for the transport of high rate data streams.

While highly advantageous on a cost basis, experimentation results show that message transmissions over power lines suffer from multi-path fading effects caused by the reflections of waves occurring at power cable junction and branch points [5], [6]. In addition, measurements show the power strength of a signal transmitted across a PLC to degrade exponentially with distance. Hence, a relay aided PLC system [7] must be employed, serving to enhance the received signal-to-noise ratio (SNR) monitored at intended receivers, and thus leading to a significant enhancement in the throughput capacity rate attainable for the transport of messages across the PLC.

However, only a limited number of studies have been published addressing the analysis and design of such relay-aided PLC network systems [8], [9], [10]. The choice of carrier frequency and the optimal allocation of bandwidth and power levels for a PLC system is studied in [8]. Both direct and relay-aided transmissions across a linear power line have been considered. However, the authors only consider the case under which a single relay station is employed. No attempt was made to optimize the relay aided layout and the network operation for the purpose of attaining a high throughput capacity rate. In [9], authors study the achievable information rates of the frequency selective channel characterizing a PLC system, using amplify-and-forward and decode-and-forward schemes. The latter study however addresses only physical layer operations; it does not engage in optimizing the system's networking operation. In [10], an information theoretic analysis of a multi-hop PLC is conducted. Although authors assume a Time Division Multiple Access (TDMA) scheduling, as used in this paper, the authors did not provide a solution to the optimal configuration of the PLC system; no methods have been presented for network system design, including the configuration of the number of relay stations and the setting of the TDMA spatial reuse factor.

In this paper, we study the design of a relay aided PLC

system, such as one that uses the HomePlug AV standard. As specified by the latter, assume the sharing of bandwidth resources across a PLC line by active relay stations to be governed by the use of a spatial TDMA (Time Division Multiple Access) scheduling scheme. We note that the HomePlug AV standard based system aims to achieve a throughput rate level of the order of hundreds of Mbps. It is thus essential to implement a relay based networking operation that is capable of achieving high throughput rate levels, as targeted by the design considered in this paper.

We consider a power line which is connected at one end to a gateway station that is used to control system operations, and to receive the message flows generated by an active home station device. We consider a period of time during which one of the stations becomes active, and is therefore interested in transporting messages to the gateway station. To attain high throughput rate, it is generally necessary to select a certain set of attached stations that are located between the active source station and the gateway sink station to act as Relay Stations (RSs). The latter forward packets across the relay backbone network towards the gateway station. We plan the relay network operation in such a way that a properly selected spatial reuse level is employed so that, when advantageous, multiple relay stations can transmit messages at the same time to their uplink neighboring RSs.

The analyses presented in this paper are used to determine the optimal joint settings of the number of RSs that should be configured, their locations, as well as the best spatial reuse level to be employed by the TDMA scheme. We note that methodologies for analyzing the capacity of a linear network have been proposed in [11]. The authors do not assume the use of any underlining scheduling scheme; they also do not direct their design approach to specifically accommodate the characteristics of the PLC channel. In contrast with the study provided in our paper, the referenced study does not engage in the detailed design of the network, including the joint setting of the TDMA scheme and the locations of activated relay stations. In this paper, we propose a numerically efficient algorithm for calculating the near-optimal configuration of a PLC network. For illustrative PLC network layouts, for which we obtain through exhaustive (brute force) to calculate optimal solutions, we demonstrate that the network layout results obtained through the use of the proposed algorithm yield PLC networks whose performance behavior is very close to that exhibited by the optimal system.

This paper is organized as follows. In Section II, the PLC system model is presented; we describe the structure of the involved TDMA scheduling scheme, and present a model for the PLC channel. The proposed algorithm, which is used to calculate the optimal system configuration, is described in Section III. The performance behavior of PLC network systems that are configured in accordance with the parameters computed through the use of the presented algorithm is illustrated in Section IV. Our conclusions are presented in Section V.

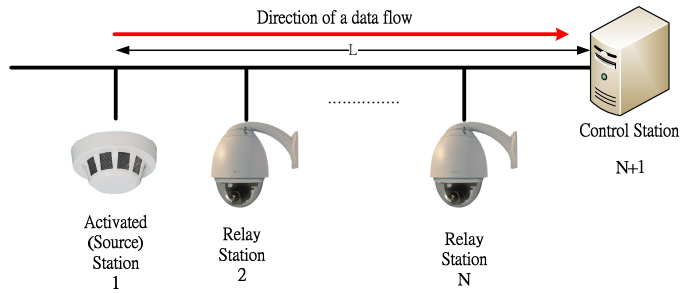

Fig. 1. A power line communication system for the supported of home networking

II. System Model

We consider the linear PLC based home network layout illustrated in Fig.1. Stations are deployed along a linear power line. They can serve to monitor and collect environmental status parameters such as temperature, humidity, or invasion signals. Each station, once activated, as may be the case when it detects exception or anomalous conditions, generated status messages or messages flows which it will then wish to transport across the PLC communications network to the control station, which often acts as a gateway station to an infrastructure backbone system. Once receiving the information, the control station can resolve the detected condition by issuing messages that control relevant devices.

Multiple stations, whose number is set equal to N_s, are attached to the PLC line. During an underlying period of time only K stations are active as message source nodes, having message flows to send to the control station. Under an "external TDMA" scheduling scheme, each one of the K active stations is allocated a time period within each time frame to use for its data transmission. As shown in Fig. 2, the latter time frame consists of K time periods, identified as beacon periods. The "external time frame" is depicted as a super-period. Each internal time period within a beacon period is identified as a "TDMA region." Within this internal TDMA period, a single active source station is scheduled to send its messages to the control station. The latter transport proceeds in in accordance with a TDMA scheduling scheme, making use of the establishment of M mini-slots during each internal TDMA period (i.e., a TDMA region).

In this paper, we focus on the design of a network that serves to support the transport of messages from a single active station to the control station during the TDMA region. The analysis applies in a similar manner to configuring an optimal relay backbone configuration for any active user station. We assume the active station to be located at a distance L away from the control station. Each one of the N_s stations can be employed as a relay station (RS) in forming a relay backbone network that is used to forward the messages issued by the source station to the gateway node. We set the number of activated stations to be equal to N; it consists of the active source station and of a total of $N-1$ stations that are set to act as RSs. Such a RS is set to receive a message from

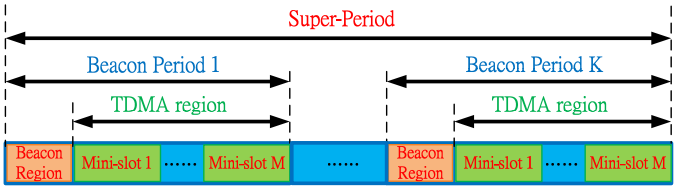

Fig. 2. TDMA frame structure of a PLC network

a downstream (i.e., away from the gateway) node (which is a RS or a source station) during a specified mini-slot, and then forward this message to an upstream (i.e., closer to the gateway) RS or directly to the control (gateway) station during another specified mini-slot. In accordance with the HomePlug AV standard, the allocation of these TDMA mini-slots to active nodes (i.e., backbone RSs and source station) for forwarding purposes is announced within control packets that are broadcasted by the control station during established control beacon periods.

To reach the control station while reliably transmitting messages at a high throughput capacity rate, the active station transmits message flows to the control station through the aid of $N-1$ selected RS nodes. To simplify, we assume that RS nodes, if any, are equally spaced between the source station and the control station. We note that the model can be extended to account for non uniform locations by extending the approach described in the following. The source station and the selected relay stations are indexed in an ascending order, starting with the source station. If $N=1$, the activate station is scheduled to transmit its messages directly to the control station. If $N>1$, RS nodes are used and then, as noted above, the internal TDMA period is divided into M mini-slots. In each mini-slot, a subset of RS nodes is activated, so that the stations that belong to this subset proceed then to transmit their messages. In this manner, messages belonging to a flow issued by the source station are relayed by the designated RS nodes, while the latter share the medium in following a spatial reuse-M TDMA scheduling operation. In this manner, during mini-slot i, the set of activated stations $\Gamma^{(i)}$ is expressed as:

$$\Gamma^{(i)} = \{i + zM | [z \in \{0\} \cup \mathbb{N}] \wedge [i + zM \leq N]\} \quad i = 1...M. \tag{1}$$

Next, we specify the channel model for the power line communications link. Messages that are transmitted across a power line medium have been shown to experience multi-path fading [5], [6], induced by wave reflections occurring at branches of a power cable. Currently employed models express the consequent power signal attenuation function incurred over a link to be approximated as:

$$A(d, f) = e^{-2(a_0 + a_1 f^s)d}, \tag{2}$$

where d is the length of the link connecting the signal transmitter and its receiver stations, and f is the carrier frequency. The coefficients a_0, a_1 , and s are obtained through the use of a least square estimation method, by fitting measurement data using linear functions [5]. Typical values for the s parameter are between 0.7 and 1. The values of a_0 and a_1 depend on the system configuration. Values of a_0 ranges from 6.0×10^{-3} to 10.0×10^{-3} and values of a_1 ranges from 3.0×10^{-9} to 3.0×10^{-7}.

The power spectral density of the background noise process is expressed as:

$$10 log_{10} N(f) = b - c f^u \text{(dBm/Hz)}, \tag{3}$$

where b assumes values that range from -94 to -124; values assumed by c are between -94 to -105; and values of u are between -0.4 to -0.6.

Under the broadband transmission technology that follows the HomePlug AV Standard, the throughput rate capacity attained across a link that connects in a direct manner an active source and the control station, has been shown to be calculated as follows (through averaging, over the channel's frequency band, of the rate value attainable by using Shannon's capacity rate formula for an AWGN channel):

$$R = \int_{f_{min}}^{f_{max}} log_2\Big(1 + \frac{P(f)A(L,f)}{N(f)}\Big) df \tag{4}$$

where f_{min} and f_{max} respectively specify the lower and the upper bound values for the channel's transport frequency band. $P(f)$ represents the allocation profile of the transmit power over frequency. In the following, we assume a constant transmit power level, so that $P(f) = P_t \; \forall f$.

Based on Eq. (2) and Eq. (4), the end-to-end throughput capacity rate $CB(m,n)$ for the multi-hop TDMA reuse-M operation is expressed as follows. We note that the active source transmits its messages to the control station by using $N-1$ uniformly distributed intermediate RS nodes. The reuse-M TDMA scheme is used to spatially schedule the flow of message transmissions executed across the store-and-forward tandem chain of serially interconnected RS nodes. It is noted that the maximum rate at which the source station can transport a flow of packets across this route to the control station is equal to the data capacity rate of the chain's link whose capacity value is the lowest one (of all the route's links). Hence, the network's capacity rate is attained by calculating the minimum rate over all the links included in the synthesized RS backbone network:

$$CB(m,n) = \min_{k=1...n} \frac{1}{m} \int_{f_{min}}^{f_{max}} log_2\left(1 + \frac{P_t A(\frac{L}{n}, f)}{N(f) + \sum\limits_{\substack{j \neq k \\ j \in \Gamma(k)}} P_t A(d(j, k+1), f)}\right) df. \tag{5}$$

The second term in the denominator represents the aggregate interference power level monitored by the receiver of station k (i.e. the receiver of station $k+1$). $\Gamma(k)$ denotes the set of stations j that transmit their packets simultaneously with

station k; $d(j,k+1)$ is the distance between stations j and $k+1$. Since relay stations assume positions along the cable in accordance with a uniform distribution function, $d(j,k+1)$ is set equal to $\frac{|j-k-1|L}{N}$.

Our objective is to maximize the attained throughput rate $CB(m,n)$, by proper selection of the number of employed RS nodes $N-1$ and by jointly setting the best value for the reuse factor M. Due to the nonlinear and relatively complex non-concave characteristic of the objective function (5), the design of the best relay backbone system is expressed as a discrete combinatorial optimization problem for which no apparent efficient solution procedure is available. Consequently, we propose in the following a computationally efficient algorithm for obtaining an approximate solution to this optimization problem. We illustrate the precision of the solutions obtained through the use of this algorithm by comparing them, for certain illustrative system scenarios, with optimal solutions that are obtained through exhaustive (brute-force) calculations. We show the algorithm to provide solutions that produce performance results that are very close to those exhibited by the optimal ones.

III. The Relay Backbone Synthesis Algorithm

In this section, we provide a step-by-step description of the proposed algorithm. It is identified as the Relay Backbone Synthesis Algorithm (RBSA). To synthesize the layout of the relay backbone network and to jointly implement the proper reuse-M TDMA scheduling scheme, we proceed to determine the joint values for the optimal number of selected RS nodes N^*-1 and of the TDMA reuse factor M^*, aiming to maximize the end-to-end throughput capacity rate attained along the relay backbone network:

1) Compute the attainable value of the throughput capacity rate for the setting $N=M$, under which each (source or relay) station is assigned a dedicated mini-slot during which no other station is allowed to transmit its messages; hence, no interference signals are generated. The optimal value of the inter-relay distance to be used under such an operation is denoted as D_0, and is given as:

$$D_0^* = \underset{D}{\text{argmax}} \frac{D}{L} \int_{f_{min}}^{f_{max}} log_2\left(1+\frac{P_t e^{-2(a_0+a_1 f^s)D}}{N(f)}\right) df. \tag{6}$$

Let

$$N_0^* = M_0^* = \underset{n\in\left\{\left\lfloor \frac{L}{D_0^*}\right\rfloor, \left\lceil \frac{L}{D_0^*}\right\rceil\right\}}{\text{argmax}} C_0(n), \tag{7}$$

where

$$C_0(n) = \frac{1}{n}\int_{f_{min}}^{f_{max}} log_2\left(1+\frac{P_t e^{-2(a_0+a_1 f^s)\frac{L}{n}}}{N(f)}\right) df. \tag{8}$$

2) For the operational case under which we set $N>M$, solve the following equation for $G>0$ (which represents the distance of the closest interferer):

$$\int_{f_{min}}^{f_{max}} N(f) df = \int_{f_{min}}^{f_{max}} P_t e^{-2(a_0+a_1 f^s)G} df. \tag{9}$$

3) Solve the following optimization problem:

$$D_1^* = \underset{D}{\text{argmax}} \frac{1}{\frac{G}{D}+1} \int_{f_{min}}^{f_{max}} log_2\left(1+\frac{P_t e^{-2(a_0+a_1 f^s)D}}{2N(f)}\right) df. \tag{10}$$

4) Find the optimal number of RSs N_1^*-1 and the optimal reuse factor M_1^* when $N>M$:
Let

$$C_1(m,n) = \frac{1}{m}\int_{f_{min}}^{f_{max}} log_2\left(1+\frac{P_t e^{-2(a_0+a_1 f^s)\frac{L}{n}}}{N(f)+P_t e^{-2(a_0+a_1 f^s)(m-1)\frac{L}{n}}}\right) df. \tag{11}$$

The optimal values of (N_1^*, M_1^*) are computed as

$$(N_1^*, M_1^*) = \underset{\substack{n\in\left\{\left\lfloor \frac{L}{D_1^*}\right\rfloor, \left\lceil \frac{L}{D_1^*}\right\rceil\right\} \\ m\in\left\{\left\lfloor \frac{G}{D_1^*}+1\right\rfloor, \left\lceil \frac{G}{D_1^*}+1\right\rceil\right\}}}{\text{argmax}} C_1(m,n). \tag{12}$$

5) Select the optimal values for N and M by comparing the performance results obtained above for the two cases: the case where $N=M$ and the case for which we set $N>M$:
   a) If $C_1(N_1^*, M_1^*) > C_0(N_0^*)$, choose $(N^*, M^*) = (N_1^*, M_1^*)$;
   b) else, choose $(N^*, M^*) = (N_0^*, M_0^*)$, whereby $N_0^* = M_0^*$.

In Step (1), we evaluate the maximum throughput rate capacity when no RS (or source) nodes are scheduled to simultaneously transmit their messages, so that $N=M$. In this case, we employ an efficient bisection numerical method [12] to solve Eq. (6). While the objective function in Eq. (6) is generally not a concave function of D, we have observed it, through our execution of numerous numerical calculations over a wide range of selected parameter values (within the bounds indicated above in defining the channel model), to exhibit quasi-concavity functionality. This behavior facilitates the efficient use of a bi-section numerical method, so that a solution is obtained in a polynomial manner. It is noted that in using this method to iteratively obtain the optimal solution for D, we solve a sequence of convex feasibility problems [12], each characterized by time complexity of the order $log_2(\frac{u-l}{\epsilon})$, where ϵ is the prescribed error tolerance, and $u(l)$ are upper (lower) bounds on the value of the objective function. The values of $u = \int_{f_{min}}^{f_{max}} log_2\big(1+\frac{P_t}{N(f)}\big) df$ and $l=0$ present trivial upper and lower bounds, respectively, for the objective function in Eq. (6); they can be used in the initiation phase of the iterative bisection numerical method.

Steps (2)-(4) are used to solve for the highest attainable value for the throughput capacity rate $C_1(m,n)$ when simul-

taneous nodal transmissions are scheduled, so that $M < N$. We start the computation by approximating the interference power monitored at each receiving RS node to be dominated by the interference caused by the power of the message signal received from the transmission performed at the same time by the closest RS node. The latter is located at a distance G from the underlying receiving RS node. Under a reuse-M operation, we obtain $G = (M-1)D$. Noting that our objective is to compute the best value for D, we use the following approach to obtain an approximate value for G. Inspired by a method used in [13] for a VANET system, we assume the maximum throughput rate value to be attained when the receiving process at a RS node is at a state which is close to the boundary of two operational modes: the noise dominant mode and the interference dominant mode. Consequently, we set in Step (2) the dominating interference power monitored at a receiving RS node to be equal to the value of its experienced noise power. We use this equality to obtain the value of G. Since the right hand side of Eq. (9) is a non-increasing function of G , the equation can be efficiently solved by using a bisection based numerical optimization method.

Having calculated G, we set $M = \frac{G}{D} + 1$; we also set the interference power term to be equal to $N(f)$. Consequently, we obtain an expression for the throughput rate as a function of D. We solve for the optimal value of D that yields the highest throughput rate, as expressed by equation (10). For this purpose, we have again used a bisection numerical optimization approach. The comments made above relating to the complexity of the bisection method apply here as well.

In Step (4), we use a numerically efficient computation to calculate the desired integer values (N_1^*, M_1^*), by assuming them to be closely related to the corresponding non-integral values that are obtained by setting $D = D_1^*$. We compare the throughput capacity rate values attained when we set N and M to each assume the two closest integer values of $\frac{L}{D_1^*}$ and of $\frac{G}{D_1^*} + 1$, respectively. Accordingly, four values of $C_1(m, n)$ are calculated and compared. The values that yield the best throughput rate performance level are selected. We expect such an approximation to yield parameter values that will lead to throughput rate performance that is close to that expressed by the above calculated maximum throughput rate level.

Finally, in Step (5), we compare the throughput capacity rate attained under the case $N = M$ (whereby RS nodes are scheduled to transmit their messages in an independent fashion) vs. that achieved under the $N > M$ case (whereby spatial reuse operation is invoked). The case that yields the highest throughput rate value is identified and used to calculate the system's throughput capacity rate. The associated values of N and M are selected and used to set the optimal configuration for the relay-aided TDMA PLC system.

IV. Performance Illustrations

In this section, we demonstrate the performance effectiveness of the suboptimal solutions derived by using the proposed algorithm. We compare the resulting performance with that obtained by setting system parameters to yield the highest feasible throughput rate. The latter values are obtained through the execution of exhaustive (brute-force) calculations.

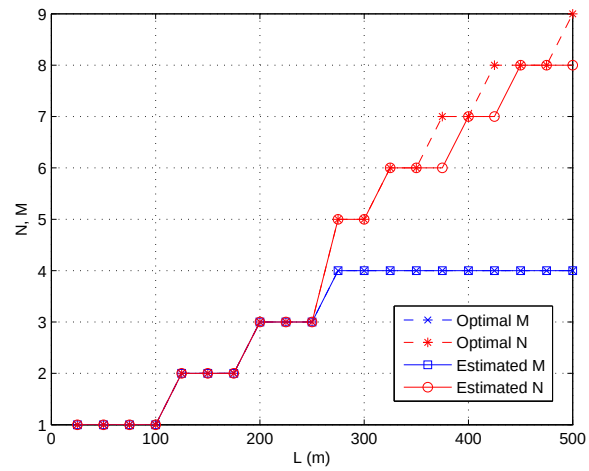

Fig. 3. Optimal vs. estimated preferred number of forwarding stations and spatial reuse factors

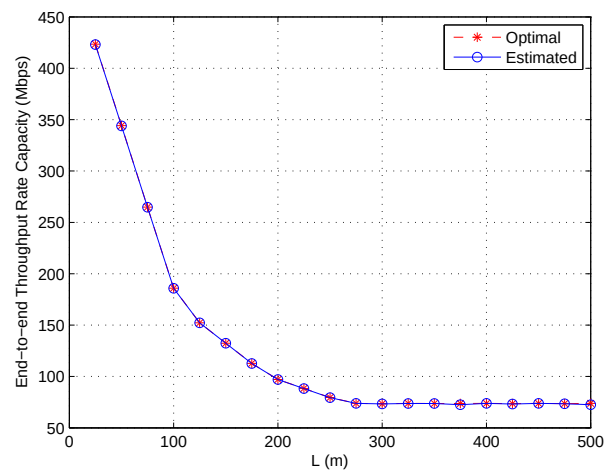

Fig. 4. Optimal vs. estimated attained end-to-end throughput capacity rate

The parameters for the illustrative PLC system are set as follows. The operating frequency band is specified as $f_{min} = 2MHz$ and $f_{max} = 28MHz$. The power allocation profile is $P(f) = 10^{-2}(mW/Hz)\ \forall f$. The parameters for the channel model are: $a_0 = 9.33 \times 10^{-3}$, $a_1 = 5.1 \times 10^{-3}$, $s = 0.7$, $b = -105$, $c = 90$, and $u = -0.5$.

As observed in Fig. 3, the settings for the best N and M values as calculated by using the proposed algorithm (and identified as the estimated values) closely match the optimal values. Such excellent match has been observed to hold uniformly, for all examined values of L. In Fig. 4, we further observe, for all examined values of L, a perfect match in the throughput capacity rate values attained in synthesizing the system by using the estimated suboptimal solutions and by employing the optimal solutions. It is interesting to note

that for the underlying system, with cable lengths satisfying $L \leq 500$(m), under the optimal setting, at most two stations (i.e., a source station and a RS node; or two RS nodes) should be scheduled to transmit their messages at the same time. For example, for $L = 300$ (m), under both the optimal solution and the one obtained by using the algorithm, the same configuration is derived: the system is synthesized to provide $(N^*, M^*) = (5, 4)$. Similarly, identical designs are also derived for $L = 450$ (m), whereby the optimal and estimated settings are equal to $(N^*, M^*) = (8, 4)$. These results well confirm our performance evaluation approach, showing that the closest interferer assumption and the other computational approximations used for the specification of the presented lower computational complexity approach to the optimal synthesis of the PLC system, lead to a system whose performance is very close to that exhibited by the optimal configuration.

The results shown in Fig. 3 point out a threshold-based approach to the design of the optimal backbone network for the PLC system. It demonstrates the dependence of the configured (N, M) values on L. For a short transport distance ($L \leq 100$(m)), a direct transmission is preferable. We show that then the use of intermediate relay stations would lead to limited improvement in the throughput capacity rate while requiring high time sharing ratios, resulting in lower overall throughput rates. For a medium-length transport distance (100(m)$< L \leq 250$(m)), multiple RS nodes should be employed to enhance the throughput capacity rate offered by the PLC system. However, due to the close location proximity of activated stations, it is then desirable to configure these stations to operate in an interference-free environment, avoiding simultaneous transmissions and thus inducing the setting $(N = M)$. For longer transport distances ($L > 250$(m)), multiple RS nodes must be activated and set to forward messages in a time simultaneous fashion. Such an operation serves to enhance the realized throughput capacity rate by invoking higher spatial reuse ratios. However, as noted above, for transport distances that satisfy $L \leq 500$(m), at most two RS nodes are activated. Much degraded throughput rate levels are attained for longer transport distance levels, associated with the use of longer PLC cable systems.

V. Conclusions

In this paper, we consider a power line communications (PLC) system that is used to transport messages from an active user home station to a control station. Other stations can be configured to act as store-and-forward relay stations (RSs), serving to forward messages transported across the cable for eventual reception at the the control station. To achieve a high system throughput rate, a spatial reuse-M TDMA scheduling scheme is invoked. We present a computationally efficient algorithm that is used to calculate effective values for the number of stations that should be activated as RS nodes and for the spatial reuse level M that should be jointly employed. This computation yields a lookup table that identifies the optimal parameter sets, and hence system configuration, to be used as a function of the distance between the active source station and the destination control station. In considering an illustrative typical such PLC system, we show our algorithm to yield system parameter and layout configurations and throughput rate performance behavior that are very close to those obtained under optimal designs.

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