A Multi-channel Medium Access Control Protocol for Vehicular Power Line Communication Systems

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***Abstract*—In-vehicle communications are emerging to play an important role in the continued development of reliable and efficient X-by-wire applications in new vehicles. Since vehicle devices, sensors and electronic control unit (ECU) are already connected to power wires, the advancement of power line communications can provide a very low cost and virtually free platform for in-vehicle communications. In this paper, we propose a medium access control (MAC) protocol for vehicular power line communication systems, where multiple nodes are competing for transmission over the direct current (DC) power line. The proposed protocol uses a combination of time and frequency multiplexing and consists of two key features: (i) a distributed channel selection policy to arbitrate packet transmission across different channels, and provide robustness against interference and noise and (ii) a distributed collision resolution algorithm to allow efficient nodes completion over selected channels. Specifically, the collision resolution algorithm is optimized with respect to the channel policy such that the success probability of transmission in each channel is maximized. Numerical results are also supplemented to validate the performance of the proposed protocol and provide useful guidelines for developing a robust contention-based MAC protocol for vehicular power line communication systems.**

I. INTRODUCTION

Over the past few years, we have witnessed an increasing interest in the use of power line communication (PLC) for home automation systems, automatic meter reading, real-time energy management systems, and many other applications. Recent research efforts have been focusing on the use of in-vehicle DC power lines as a physical medium for data communications [1]–[5]. PLC is a promising method that can potentially reduce the complexity, cost, weight of the wiring harness and fuel consumption of the vehicles.

The measurements of vehicular power line communication (VPLC) channels [1]–[4], however, indicates that there are still a number of challenges for communications over power wires. These challenges include channel transfer functions varying in both time and frequency and experiencing deep notches [1], [2], change of access impedance seen by communication devices varying in both time and access location [6], [7], and the presence of non-stationary impulsive noise generated by various electrical devices connected to the VPLC networks [4]. These challenges make the impact of sensing errors on the performance of the in-vehicle communications a further important issue to be considered.

Recently, a medium access control (MAC) protocol, named as *contention detection and resolution* (CDR), has been proposed for VPLC in [5]. To the best of our knowledge, this CDR protocol is the only existing well-established random access protocol designed for VPLC systems. The contention mechanism in CDR works as follows: Nodes use a n-bit random arbitration register (RAR) to randomize their access to the medium. Initially, a node waits until the power line is idle, followed by a random delay chosen uniformly from $[0, (n-1)\sigma_{slot}]$, where σ_{slot} is the duration of a single time slot and n is the number of slots. After that, all nodes in the contention switch between carrier sense and carrier transmission modes according to the content of their RARs, and drop out of contention if they are listening and hearing a carrier on the power line. The aim of the CDR is to have only one node remaining at the end of the contention to access the power line channel. Existing literature, e.g., [5], analyzed the collision probability of the proposed MAC with the assumption of perfect sensing, and compared the CDR protocol with carrier sense multiple access with collision avoidance (CSMA/CA) protocol to show the performance improvement of using CDR protocol for VPLC systems.

In this paper, based on the challenges of VPLC mentioned earlier, we present a MAC protocol that provides access by resolving the contention using a combination of time and frequency multiplexing. In brief, the proposed protocol works as follows: First, each transmitter selects one of the available frequency channels based on a pre-specified probability and then, on each channel, the contention is resolved over several slots in which nodes probabilistically send a carrier on the channel. At the end of the last slot, the receiver starts to scan the signal level from the first channel, and locks and receives the packets from the first non-idle frequency channel. The use of multiple frequency channels is motivated by the fact that it can potentially provide robustness against interference and noise by periodically switching between frequency channels. During a slot, nodes sensing a busy channel will retire from contention, and nodes sending carriers on a same channel will move to the next slot. Different to our preliminary studies in [8], [9], we aim to solve a joint optimization problem by deriving distributed channel selection and collision resolution such that they can reduce the chances of collision among

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transmitters. Moreover, we extend our work to investigate the effect of sensing errors on the MAC protocol performance, and apply the optimal sensing detection method to improve the MAC protocol efficiency. In essence, our proposed MAC protocol provides fast collision resolution, demonstrates high efficiency under different traffic loads, and can be implemented directly in the hardware to enhance the performance of the VPLC system.

The following summarizes our contributions and key results:

- We propose a MAC protocol by leveraging both frequency and time multiplexing to resolve the collision in in-vehicle power line communications. The optimal protocol-operational parameters can be obtained according to the channel conditions and thus maximize the overall successful probability of transmissions.
- By considering the major impact of impulsive noise in vehicular power lines, we propose a robust sensing detector designated for removing the impulses from the signal and then performing signal detection on the cleaned samples. A mathematical framework is also supplemented to analyze the performance of the proposed protocol under the presence of sensing errors.
- The analytical results show that the proposed solution outperforms existing solutions and demonstrates good performance in terms of collision probability, system throughput and delay.

The rest of the paper is organized as follows. In section II, we review the state-of-arts of related work and emphasize the motivation and importance of our work. In Section III, we describe our system assumption and present a brief description of the MAC protocol operation. Section IV provides mathematical analysis of the proposed MAC protocol, under the assumption of perfect sensing, whereas in Section V, we present the mathematical analysis of the protocol with the presence of sensing errors. We present numerical results in Section VI, and conclude in Section VII.

II. Related work

With the emerging automated tasks in vehicle domain, the development of in-vehicle communications is increasingly important and subjected to new applications. Although both wired and wireless communications have been largely deployed for supporting diverse applications, most of in-vehicle applications with time critical nature, such as brake and engine controls, still prefer dedicated wired networks for reliable transmission. According to [10], the growth of electronic components in vehicles is in the order of n^2 where n is the number of ECUs. In other words, if each node is interconnected with all the others, the number of links grows by the square of n, which means that the wired strategy will be unable to cope with the increasing use of ECUs due to the problems of weight, cost, complexity, and reliability induced by the wires and the connectors. Motivated by the use of networks where the communications are multiplexed over a shared medium, VPLC has recently been considered by physical layer researchers as a low-cost and efficient way to deliver in-vehicle communications. This solution, considering its specific characteristics, consequently requires new defined protocols for managing communications and, in particular, for granting bus access. The rest of this section provides a deeper insight on properties of physical layer and challenges that impose on communication systems, as well as related works on communication protocols with respect to VPLC.

A. Physical Layer

Understanding the characteristics of power wires in vehicle as a communication channel has been the drive for many measurement campaigns [2], [6], [7], [11]–[16]. The findings show that vehicle power lines constitute a harsh and noisy transmission medium with both time and frequency-selective channel, colored background noise, and periodic and aperiodic impulsive noise, e.g., [17], [18]. These characteristics make obtaining deterministic description of the channel and its noise an extremely complicated and cumbersome task. The tree-shaped topologies of the cable bundles, as well as type, size and length of cables in the bundle itself, are also quite different, which creates further diversity of channel characteristic among different vehicles. Therefore, a proper modelling of a channel would need quite a lot of detailed information on type and length of cables used to connect different nodes as well as their bundling which can be a source of some characteristics specially cross transmission interferences. In addition, the body of a vehicle as the return path for many ground signals affects the channel characteristics which is different from one vehicle to another. Furthermore, the highly variable activation schedules of electrical functions such as windshield wipers or antilock braking systems (ABS), which produce sharp modifications in the circuits' load impedances over brief time intervals [19], can impose serious challenges on communication devices or even interrupt communications. These noise sources would be also largely different from one vehicle to another, since not all the vehicles use the same devices and in the same manner. In consequence, even if modelling the channel in a vehicle - however cumbersome - is achieved, the deterministic description and any derived conclusion thereof, would be very specific to that certain model of vehicle and not useful for other vehicles. All these issues lead into a need for extra considerations in protocol design and necessitates a protocol which can address VPLC channel challenges in a rather more general manner.

Characteristic measurements of physical layer are often restricted by the access to vehicles for performing the measurement test. Existing measurements have been done over various vehicles, such as [2], [6], [20] for Internal Combustion Engine Vehicle (ICE) and [3], [7], [16] for Electric or Hybrid Electric Vehicle. In essence, we can learn that the channel attenuations are very link dependent and also varied from car to car. In a broader perspective, it can be observed that all the channels are fairly frequency selective with random deep notches. Readers can refer these papers for details of measurement set-ups, results, calculations and discussion.

To further investigate the issue of noise on the signal being transmitted through the channel, a sample of measurements in time domain showing the inflicted noise on the signal can be found in [4]. Specifically, we can observe different events happening which have inflicted noise upon the signal. Some of these noise events are rather periodical, which could be due to operation of a certain device and hence rather predictable. However, some others are neither periodical nor predictable. These noises are most likely due to activation of different devices or loads inside the vehicle as they have a different nature as well as different effect on the signal. Therefore, a communication protocol that ascertains robustness and reliability of the communication despite all these challenges in physical layer plays an important role not only in effectiveness but also in practicality of using power wires for communications purpose inside vehicles.

B. MAC Layer

Besides the challenges in physical layer, the requirements of applications with time critical nature can be fundamentally different from that of applications for which current MAC protocols are designed [21]. For example, energy is a valuable resource of sensor devices and most existing MAC protocols are optimized to conserve energy, trade off latency and throughput, etc. These protocols are typically not suitable when a vehicular application demands real-time requirement, because the energy sources are not as critically in shortage as in other scenarios. According to [22], some critical control messages in a car need to be delivered within a very small delay such as 100 µs. The challenge in using existing solutions, such as IEEE 802.3 for Ethernet, as the universal in-vehicle network lies in meeting the real-time requirements of various time-critical car applications, since they all experience a longer delay[1] and do not provide the quality-of-service (QoS) guarantee on the minimum delay or bandwidth. The wireless interconnection of sensors and other devices within the vehicle, such as radio frequency in the IEEE 802.x based solutions [23], [24], is also being investigated. Although there are advantages to use wireless transmission, such as lessening weight and physical network complexity, in-vehicle wireless devices still require connection to the electrical power source in the vehicle, which mitigates this advantage [25]. There are also raising concerns about security in wireless networks, such as eavesdropping on a in-vehicle network, and reverse engineering to jam false data, are possible in a moving vehicle. This particularly important, since the in-vehicle network is safety-critical and it is imperative to avoid security problems which lead to disastrous safety implications. In essence, if reliability or security gives higher priorities in in-vehicle communications, communication protocols need to be re-designed from the application's perspective.

There have been state-of-art works on in-vehicle MAC protocol design as it is a fundamental issue to enable channel access control that make it possible for several ECUs or network nodes to communicate in a multiple access network incorporating a shared medium, e.g., twisted pair cable, and thus support upper layer protocols for application services. Local Interconnect Network (LIN) [26] is a low cost serial bus network used for distributed body control electronic systems in vehicle. It is a single master/multiple slave architecture. One node, termed as master, possesses an accurate clock and drives the communication by polling the other nodes - the slaves - periodically. As it is time triggered, message latency is guaranteed. The LIN can be implemented using just a single wire. However, since the speed is only 20Kbit/s, it is considered to be most appropriate for less time critical applications, such as controlling doors (e.g., door locks, opening/closing windows) or seats (e.g., seat position motors, occupancy control). Controller Area Network (CAN) [27] is a priority-based bus which allows to provide a bounded communication delay for each message priority. The MAC protocol of CAN uses Carrier Sense Multiple Access with Collision Detection (CSMA/CD) with bit by bit non-destructive arbitration over the Identifier Field which serves as priority. Therefore, the transmission delay for higher priority messages can be guaranteed. However the use of bit-wise arbitration scheme intrinsically limits the bit rate of CAN as the bit time must be long enough to cover the propagation delay on the whole network. It supports speeds of up to 1Mb/s, suitable for real time control applications. CAN needs to be implemented using two wires and the event triggered nature is very efficient in terms of bandwidth usage. FlexRay [28] is a protocol that combines time triggered (primary) and event triggered messaging for point-to-point communications. It is being developed by BMW and DaimlerChrysler with Philips and Motorola, and its purpose is to provide X-by-Wire applications with deterministic real-time and reliable communications. The FlexRay can support a net data rate of 5Mbps (10 Mbps gross). It is a protocol in Bus architectures for safety-critical embedded systems and advanced control functions.

Our contribution in this paper is that we propose a contention resolution method for vehicular power line communications by leveraging both frequency and time domain selections to resolve the bus access collision. To the best of our knowledge, this is the first work that considers time and frequency multiplexing in optimizing the VPLC performance. Hence these results will potentially have a broad impact across a range of industry areas, including in-vehicle communications and control systems, etc.

III. System Assumption and the proposed multi-channel contention resolution method

We consider a VPLC network in which N nodes are connected to the harness. Time is divided into a fixed-size transmission cycles, where multiple frequency channels can be used by the senders or receivers. Despite the using of multiple channels, we assume that each node includes one signal feed and receive ports. We further assume all nodes in the VPLC network are time synchronized. Fig. 1 depicts the structure of a single transmission cycle. First, the contention

[1] A 1518-byte Ethernet message would take 122.08 µs to be forwarded in a 100 Mbps Ethernet switch.

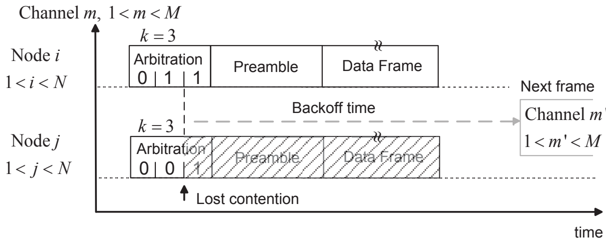

Fig. 1. A view of a single transmission cycle.

between senders is resolved on the frequency domain where each sender, at the beginning of the transmission cycle, picks up a channel randomly. Then, if more than one sender select the same channel, the contention is resolved over number of slots by randomly performing one of the two following actions in each slot: a carrier sense (*cs*) operation or a carrier transmission (*ct*) operation. At each time slot, the sender defers its transmission to the next transmission cycle if it senses the channel busy. But if the sender does not hear the carrier, it stays on the contention. At the end of the last slot, the remaining senders transmit a long preamble on their selected channel. After that, the receiver samples the signal level from the first channel, and locks and receives the packets from the first non-idle frequency channel. It is worth noting that the arbitration procedure relies on the fact that a sending node monitors the bus while transmitting. The signal must be able to propagate to the most remote node and return back before the bit value is decided. This requires the bit time to be at least twice as long as the propagation delay.

An example of the collision resolution algorithm performed between contending nodes on each channel, is given in Fig. 2. Assume there are three time slots, and the left and right branches correspond to the *ct* and *cs* operations, respectively. In the first slot, each node chooses *ct* with probability q, and only nodes who choose *cs* and sense the channel is occupied will retire from contention. In the second slot, a node chooses *ct* with probability q_1 if it has emitted a carrier in the first slot, and with probability q_0 otherwise. This procedure repeats for the next slots. For the case of k contention slots, if we describe the whole process with a set of k binary digits where bit 1 and 0 correspond to the *ct* and *cs* operations, respectively, we can conclude that a node with the largest value (i.e. high priority) wins the contention. In the following sections, we focus on the probabilistic analysis of the proposed MAC protocol and provide insights of designing protocol parameters to cope with contention and sensing errors. Table I lists the parameters used for performance analysis.

IV. Performance Analysis under Perfect Sensing

Consider a system scenario, where at a given time, n nodes try to transmit packets over the DC power line. We assume the value of n is not known to the nodes, but its probability mass function is known to all nodes in the network, and can

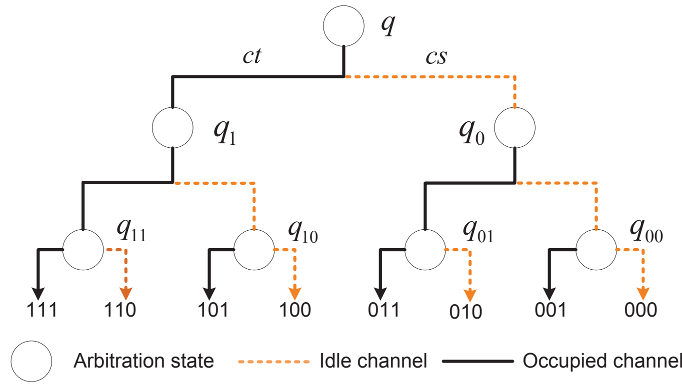

Fig. 2. Illustration of the collision resolution algorithm performed on each channel.

TABLE I
Parameters used for performance analysis

Parameter	Description
M	Number of channels
N	Number of nodes connected to the the DC power line
n	Number of nodes trying to transmit packets over the DC power line
k	Number of time slots to solve contention
T	Number of transmission circles
$p_N(n)$	Probability mass function of n
$p_m, 1 \le m \le M$	Probability that the m-th channel is selected by a sender
$\mathbf{p} = (p_1, p_2, \ldots, p_M)$	Channel selection distribution
$q^{(m)}$	Probability vector to resolve the contention on the m-th channel
$\mathbf{q} = [q^{(1)}, q^{(2)}, \ldots, q^{(M)}]^T$	Probability vectors on all M channels
$p_N^{(m)}(l)$	Probability mass function of l contending nodes on the m-th channel
$g^{(m)}(z)$	Probability generating function (PGF) of the number of contending nodes on the m-th channel
$g_c^{(m)}(z)$	PGF of the number of contending nodes with the signaling pattern c in the first t slots
$\tau_{q^{(m)}}(i)$	Probability that the contention is successfully resolved on the m-th channel when i nodes select that channel
$\pi_{\mathbf{p}}(n)$	Successful transmission probability given n contending nodes
$\rho_w(n)$	Throughput of the w-th received packet given n contending nodes
p_{md}	Probability of miss detection
p_{fa}	Probability of false alarm
λ	Threshold of the energy detector

be expressed as

$$p_N(n) = \frac{1}{\zeta(\gamma) n^{\gamma}} . \quad (1)$$

where $n \in \{2, \ldots, N\}$, N is the number of nodes connected to the DC-bus, and $\zeta(\gamma) = \sum_{z=2}^{N} \frac{1}{z^{\gamma}}$, where γ is the shape parameter of the distribution. This distribution is widely applied to model self-similar packet arrivals [29]. We would like to remark, however, that the analysis in this paper are valid for any other distribution of interest.

We are now ready to formulate the problem. Let $\mathbf{p} = (p_1, p_2, \ldots, p_M)$ be the channel selection distribution, where

p_m is the probability that the m-th channel is selected by a sender. Assume the collision resolution algorithm uses k slots, and let $q^{(m)}$ be the probability vector of size $\sum_{i=0}^{k-1} 2^i = 2^k - 1$, used to resolve the contention on the m-th channel. Fig. 2 gives an example of how the vector space can be calculated. Therefore, the probability vectors on all M channels can be expressed with a matrix $\mathbf{q} = [q^{(1)}, q^{(2)}, \ldots, q^{(M)}]^T$. Suppose the number of senders in the contention is n, a transmission is successful on the m-th channel if and only if:

- m is the first non-idle frequency channel, that is, $\prod_{t=0}^{m-1} (1-p_t)^n$.
- There is only one node transmitting on the m-th channel, that is, $\sum_{i=1}^{n} \binom{n}{i} (p_m)^i (1-p_m)^{n-i} \tau_{q^{(m)}}(i)$.

Therefore, the success probability is derived as

$$\pi_p(n) = \sum_{m=1}^{M} \prod_{t=0}^{m-1} (1-p_t)^n \sum_{i=1}^{n} \binom{n}{i} (p_m)^i (1-p_m)^{n-i} \tau_{q^{(m)}}(i) \,, \tag{2}$$

where $p_0 := 0$, and $\tau_{q^{(m)}}(i)$ is the probability that the contention is successfully resolved on the m-th channel when i nodes selected that channel. To further calculate $\tau_{q^{(m)}}(i)$, we need to find the probability mass function of the number of contending nodes on the m-th channel. For a given vector $\mathbf{p}$, this distribution can be expressed as

$$p_N^{(m)}(l) = \sum_{n=l}^{N} \binom{n}{l} (p_m)^l (1-p_m)^{n-l} p_N(n) \,, \tag{3}$$

where $m \in \{1, \ldots, M\}$ and $l \in \{0, \ldots, N\}$. The probability generating function (PGF) of the number of contending nodes on the m-th channel is defined as

$$g^{(m)}(z) := \mathbb{E}(z^n) = \sum_{n=0}^{N} p_N^{(m)}(n) \; z^n \,, \tag{4}$$

Now the $\tau_{q^{(m)}}(i)$ can be derived as $\frac{d}{dz} \sum_{c \in \mathcal{C}_k} g_c^{(m)}(z)|_{z=0}$, where $g_c^{(m)}(z)$ is the probability generating function (PGF) of the number of contending nodes on the m-th channel after the elapse of c time slot, and $\mathcal{C}_k$ is the set of all binary numbers of length k from the alphabet $\{0, 1\}$. It is worth noting that in order to avoid duplicated contents, the derivations of $g_c^{(m)}(z)$ and $\tau_{q^{(m)}}(i)$ can be directly referred from (18), (19) and (21) with sensing errors equals 0.

Averaging $\pi_p(n)$ over the distribution described in (1) leads to the success probability

$$\pi_p = \mathbb{E}[\pi_p(n)] = \sum_{n=2}^{N} p_N(n) \pi_p(n) \,. \tag{5}$$

Now, we try to find the probability distribution $\mathbf{p}$ and matrix $\mathbf{q}$ that maximize the success probability described in (5), i.e.,

$$\arg\max_{\mathbf{p}, \mathbf{q}} \pi_p \tag{6}$$

Algorithm 1 provides the solution and describes how we can calculate the optimal vector $q^{(m)}$ for the m-th channel, given the distribution of contenders on the m-th channel, i.e., the value of p_m is assumed to be known. It is noted that we have used the method proposed in [30] to minimize the collision probability on the m-th channel, which finds the optimum solution by approximating the collision probability with a Riemann integral.

The distribution of $\mathbf{p}$ determines the efficiency of collision resolution. For this purpose, we have chosen the truncated geometric distribution used in the design of Sift protocol [31] to achieve fast collision resolution. Sift is a randomized carrier sense multiple access (CSMA) based protocol for wireless sensor networks, where nodes use a truncated geometric distribution for selecting their contention slots. Similarly, in our protocol, senders use this geometrically-increasing probability distribution for picking their channels in the transmission cycle. Its expression for $m = 1, \ldots, M$ is given by

$$p_m = \frac{\beta^{\frac{m}{M}} - \beta^{\frac{m-1}{M}}}{\beta - 1} \,. \tag{7}$$

where β is the parameter that needs to be carefully designed. Fig. 3 illustrates the impact of various β values on the channel probabilities when $M = 10$. We have obtained these probabilities for three values: $\beta = 10$, $\beta = 100$, and $\beta = 1000$. It can be observed that the channel probabilities increase much faster as β increases. It is worth noting that our goal is to find the optimal probabilities ($\mathbf{p}$, $\mathbf{q}$) to maximize success probability (6), thus the parameter β can be adjusted to feed the optimal requirement. So in the paper, we actually address the optimization by finding the optimal ($\mathbf{p}$, $\mathbf{q}$) via numerical method and the specific value of β is out of scope of the paper.

Throughput evaluation: Suppose that the random variable T_1 denotes the number of transmission cycles required to successfully transmit the first packet. If there are n contenders,

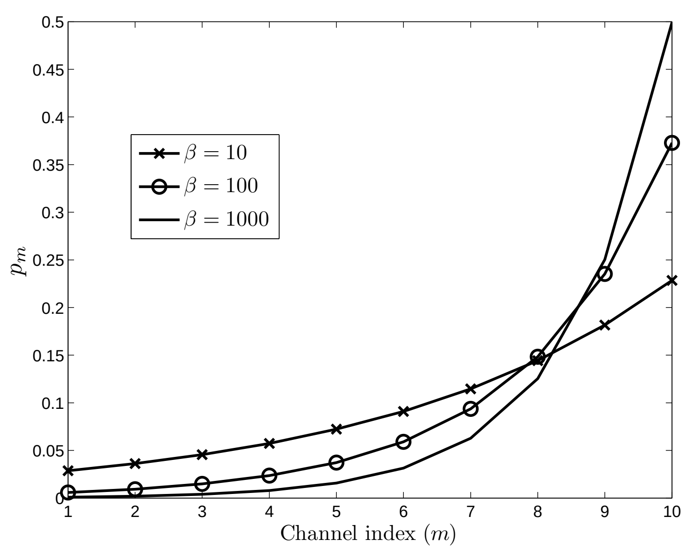

Fig. 3. Channel selection probabilities when $M = 10$ channels are available for multiple choices of β.

Algorithm 1 : Maximize success probability on the m-th frequency channel without sensing errors.

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Set $\hat{u}(z) := \sqrt{g''(z)}$  /* $g''(z)$ is the second derivative of $g(z) = \sum_{n=2}^{N} p_N^{(m)}(n) z^n$ with respect to z */
Initialization: Set $b := 2^k$, $B := 10\,b$, and $u_0 := 0$
for $i = 1$ to $B$ do
    $u_i := u_{i-1} + \hat{u}\left(\frac{i-\frac{1}{2}}{B}\right)$
end for
Set $x(0) := 0$, and $x(b) := 1$
for $t = 1$ to $b - 1$ do
    $x(t) = \frac{1}{B}\ \min\left\{i : \frac{u_i}{u_{B-1}} \geq \frac{t}{b}\right\}$
end for
Set $q^{(m)} := 1 - \frac{x\left(\frac{b}{2}\right)}{x(b)}$
for $L = 1$ to $k - 1$ do
    Set $L := 2^{k-l-1}$
    for $j = 0$ to $2^{l-1}$ do
        Convert $j$ into $l$ bits binary number $c$
        $q_c^{(m)} := \frac{x(2L(j+1)) - x(L(2j+1))}{x(2L(j+1)) - x(2Lj)}$
    end for
end for
```

then

$$\mathbb{P}(T_1 = r) = \pi_p(n)(1 - \pi_p(n))^{r-1}\,, \tag{8}$$

where $r \in \{1, 2, \dots\}$, and $\pi_p(n)$ is the probability of success described in (2) when there are n contenders. Note that T_1 describes the delay which corresponds to the first packet successfully transmitted to the receiver. By a similar argument, we find the distribution of T_w, the number of transmission cycles needed to transmit w packets to the destination. Let X_i denote the number of transmission cycles required to transmit the i-th packet, conditioned that the previous packets have been transmitted successfully. From (8), it is obvious that X_i has a geometric distribution with average $\frac{1}{\pi_p(n-i+1)}$. We can express the random variable T_w as

$$T_w = \sum_{i=1}^{w} X_i\,, \tag{9}$$

Thus, the expected value of T_w is

$$\mathbb{E}[T_w] = \sum_{i=n-w+1}^{n} \frac{1}{\pi_p(i)}\,, \tag{10}$$

with $w \in \{1, 2, \dots, n\}$. The normalized throughput under consideration is defined as a fraction of time the network is used to successfully transmit packets. Hence we have the throughput which corresponds to the w-th received packet as

$$\rho_w(n) = \frac{w\sigma_d}{\mathbb{E}[T_w]\sigma_{cycle}}\,. \tag{11}$$

where the transmission cycle duration is defined as $\sigma_{cycle} = k\sigma_s + M\sigma_c + \sigma_d$, σ_s represents the amount of time required by a node to determine the presence of the carrier on a frequency channel, σ_c is the time duration needed by the receiver to sample a frequency channel and switch to the next channel, and σ_d specifies the amount of time needed for transmitting a packet and receiving an ACK.

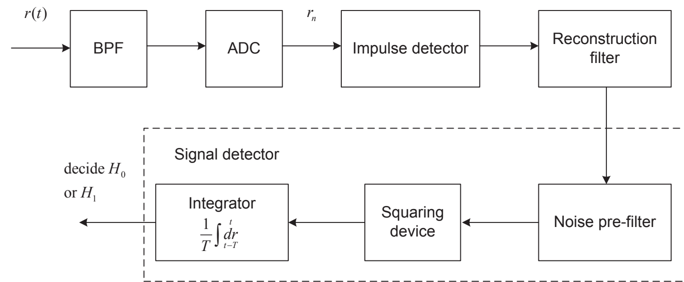


Fig. 4. Block diagram of a robust sensing module.

V. Performance Analysis under the Presence of Sensing Errors

In this section, we start by giving an overview of the sensing algorithms and discussing our design goals, then we analytically evaluate the impact of sensing errors on the performance of the proposed protocol.

A. *Impulse Noise Filtering*

The noise over DC power line contains impulse components, thus we need to consider signal detection schemes designed for non-Gaussian noise scenarios. There are several detection algorithms proposed for non-Gaussian noise in the literature [32]. However, these algorithms are either difficult to implement or time consuming to compute.

Motivated by a robust prediction and whitening method in [33], we propose a detection scheme composed of a non-linear preprocessor and a simple signal detector to reshape the designated signals into Gaussian signal. The proposed sensing module is depicted in Fig. 4, where the received signal passes through a band-pass filter (BPF) with bandwidth W and an Analog-to-Digital Converter (ADC) with sampling rate f_s, followed by a preprocessor and a signal detector. The impulse components are removed from the received signal by using the preprocessor proposed in [33], which consists of an impulse detector, followed by a reconstruction matched filter that chooses between input and predicted samples, i.e., Gaussian assumption. The impulse detector is composed of a blanking nonlinearity to mitigate the effects of the impulsive noise. We use energy detector for signal detection in which the energy of the received signal is measured over a time period and then, is compared with a predetermined threshold to determine the presence or the absence of the signal [34].

We conduct an experiment to demonstrate the effectiveness of the preprocessor. Assume the received signal is corrupted by a Gaussian noise with variance one, and impulsive noise with probability of occurrence 0.1 and variance 10. We plot the empirical cumulative distribution function (ECDF) of the received signal in Fig. 5. As can been seen, the preprocessor removes the heavy tail of the signal and thus, filters out the impulse components in the received signal. We would like to remark that any other detector of interest can also be used for signal detection.

Therefore, the signal detection problem under the output Gaussian noise can be formulated as a binary hypothesis

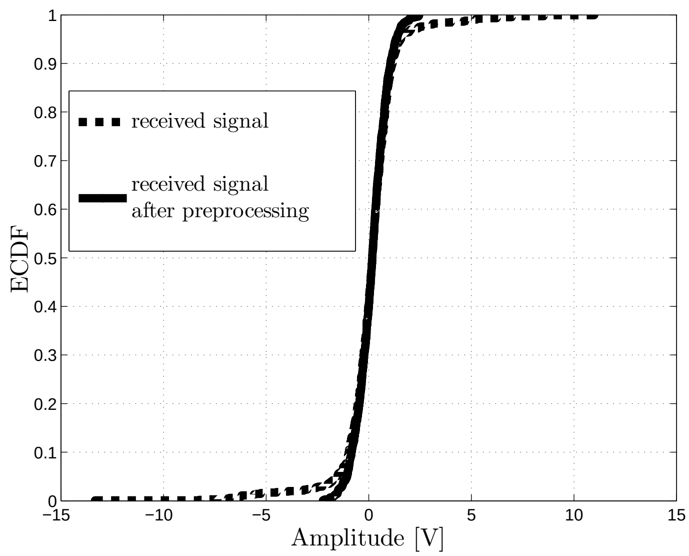


Fig. 5. ECDF of the received signal before and after preprocessing.

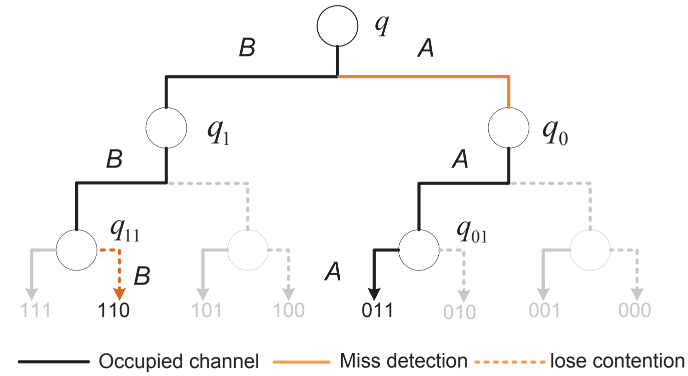


Fig. 6. Illustration of the protocol operation with imperfect sensing.

testing problem with $\mathcal{H}_0$ (noise only) or $\mathcal{H}_1$ (signal present),

$$\begin{aligned}\mathcal{H}_0 &: r(t) = n(t), \\ \mathcal{H}_1 &: r(t) = s(t) + n(t)\end{aligned} \tag{12}$$

where $n(t)$ is the noise signal at the receiver and is assumed to be an additive white Gaussian noise (AWGN), and $s(t)$ is the filtered transmitted signal. It is noted that the filtered signal $s(t)$ includes the attenuation imposed by the PLC channel transfer function $h(t)$ which has been discussed in Section II. In the absence of much knowledge concerning the input signal, it is appropriate to use an energy detector to determine the presence of a signal. The energy detector operates over a specific time interval by filtering, squaring and integrating the received signal $r(t)$. For the sake of brevity, we only provide a brief discussion of the system model. More detailed derivations of these fundamental results can be referred from [35]. Thus the probability of miss detection (p_{md}) and false alarm (p_{fa}) for energy detection are expressed as

$$p_{md} = 1 - Q_u(\sqrt{2\epsilon}, \sqrt{\lambda}), \tag{13}$$

$$p_{fa} = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)}. \tag{14}$$

where $Q_u(.,.)$ is the generalized Marcum-Q function, and $\Gamma(.,.)$ is the upper incomplete gamma function [36]. The parameter ϵ is the ratio of signal energy to one-sided noise spectral density at the receiver, and has $\epsilon = u \times \text{SNR}$, where u is the time-bandwidth product[2] and assumed to be a positive integer, and SNR is the ratio of signal energy to the noise energy of the preprocessed signal. λ is the threshold of the energy detector. It is noted that the false alarm probability does not depend on SNR or reception schemes, but directly relate to the threshold of the energy detector.

[2] $u = TW$, where T is the observation time interval in seconds, and W is the one-sided bandwidth (Hz), i.e. positive bandwidth of the low-pass (LP) signal.

B. Impact of Sensing Errors

Sensing errors are inevitable in any CSMA-based MAC protocols. There are two types of sensing errors associated with any sensing algorithms: false alarm and miss-detection. False alarms occur when idle channels are sensed to be busy, and miss detections occur when busy channels are detected idle. The performance of any detection algorithm is characterized through its receiver operating characteristic (ROC) curves [35]. ROC curves describe the tradeoff between false alarm and miss detection by plotting detection probability (p_d) versus false alarm probability (p_{fa}).

We start by giving an example of the protocol operation to show how sensing errors can affect the protocol performance. Fig. 6 shows an instance of the protocol with three slots. Assume nodes A and B have packets to transmit. In the first slot, node A selects *cs* operation whereas node B emits a carrier. In the case of perfect sensing, node A which listens to the channel, hears a carrier and loses the contention. With imperfect sensing, however, node A may not hear the carrier sent by node B, with p_{md}, and thus continues to the second slot. If this happens and both nodes emit a carrier in the second slot, the winners are determined in the last slot. As can been seen, node A emits a carrier while node B listens to the channel. If node B correctly identifies the carrier from A, it retires from the contention. Recall from Section III that nodes with the largest number win the contention. In this example, nodes A and B have chosen 011 and 110, respectively. Hence, node B has a larger binary value and wins the contention with the assumption of perfect sensing. However, the result is unknown with imperfect sensing, as in the above example node A wins the contention.

Now, we investigate the impact of sensing errors on the performance of our protocol. Suppose there are N nodes connected to the DC power line network and the number of nodes with packets follows the distribution described in (1). Furthermore, assume that sensing is not perfect, and there are sensing errors due to the channel impairments. Let $p_{fa}^{(m)}$ and

$$\pi_p(n) = \sum_{m=1}^{M} (1-q_{md}^{(m)}) \prod_{t=0}^{m-1} (1-p_t)^n (1-q_{fa}^{(t)}) \sum_{i=1}^{n} \binom{n}{i} (p_m)^i (1-p_m)^{n-i} \tau_{q^{(m)}}(i, p_{fa}^{(m)}, p_{md}^{(m)}) \,. \tag{15}$$

$p_{md}^{(m)}$ denote the false alarm and miss-detection probabilities for senders on the m-th channel, respectively. Similarly, we define $q_{fa}^{(m)}$ and $q_{md}^{(m)}$ as the probabilities of false alarm and miss detection related to the receiver on the m-th channel, respectively. Next, we calculate the success probability when there are n contenders. Assume m is the channel selected by at least one node. We say that the contention is successfully resolved on the m-th channel if and only if: (i) only one node remains on the m-th channel after the completion of the collision resolution protocol. (ii) the receiver is able to correctly determine the states of the first m channels. Hence, the success probability can be expressed as (15), where $p_0 := 0$, $p_{fa}^{(0)} := 0$, and the expected value of success probability is expressed by (5).

To derive the success probability, $\tau_{q^{(m)}}$, on the m-th channel when sensing is not perfect, we need to find the PGF of the number of contenders still in the competition after the elapse of one time slot. For simplicity of computation, we assume that, by using the preprocessor suggested in Section V-A, all nodes in the competition experience the same average SNR and therefore, we can use binomial distribution to denote the probability that i out of n nodes estimated the channel state correctly. Because this PGF depends on the number of nodes who selected *ct* operation in the previous slot, we derive its expression for the following cases:

- Case 1: If no carrier has been emitted in the first slot, then a node moves to the second slot if it senses the channel idle, which happens with probability $1-p_{fa}$. The PGF denoted as $g_0^{(m)}$, is given as

$$\begin{aligned} & g_0^{(m)}(z) \\ &= \sum_{n=0}^{N} p_N^{(m)}(n)(1-q^{(m)})^n \sum_{i=0}^{n} \binom{n}{i} (1-p_{fa}^{(m)})^i (p_{fa}^{(m)})^{n-i} z^i \\ &= \sum_{n=0}^{N} p_N^{(m)}(n) \left(1-q^{(m)}\right)^n \left(\left(1-p_{fa}^{(m)}\right) z + p_{fa}^{(m)}\right)^n \\ &= g^{(m)}\left((1-q^{(m)}) z_{fa}^{(m)}\right) , \end{aligned} \tag{16}$$

  where $z_{fa}^{(m)} := \left(1-p_{fa}^{(m)}\right) z + p_{fa}^{(m)}$, $q^{(m)}$ is the probability of transmitting a carrier in the first time slot, and $p_{fa}^{(m)}$ is the false alarm probability on the m-th channel given in (14).
- Case 2: In this case, we consider scenarios where at least one node has emitted a carrier in the previous slot. All nodes in the contention that have emitted a carrier in the first slot survive and move to the second time slot. However, nodes that have sensed the channel busy, which happens with probability $1-p_{md}$ will retire from contention. Others that have miss detected the carrier on the channel, will continue the contention. Therefore, the expression for its PGF, $g_1^{(m)}$, is expressed by

$$\begin{aligned} g_1^{(m)}(z) =& \sum_{n=1}^{N} p_N^{(m)}(n) \sum_{i=1}^{n} \binom{n}{i} \left(q^{(m)}\right)^i \left(1-q^{(m)}\right)^{n-i} z^i \\ & \sum_{j=0}^{n-i} \binom{n-i}{j} \left(p_{md}^{(m)}\right)^j \left(1-p_{md}^{(m)}\right)^{n-i-j} \; z^j \\ =& g^{(m)}\left(q^{(m)} z + (1-q^{(m)}) z_{md}^{(m)}\right) \\ & - g^{(m)}\left((1-q^{(m)}) z_{md}^{(m)}\right) , \end{aligned} \tag{17}$$

  where $z_{md}^{(m)} := p_{md}^{(m)} z + 1 - p_{md}^{(m)}$, and $p_{md}^{(m)}$ is the miss detection probability on the m-th channel defined in (13).

Let c be a t-bit binary number with bit notations from b_1 to b_t that shows the operations performed by a sender in each slot, where $b_i = 0$ or 1 denotes the events of choosing *cs* and *ct* in the i-th slot, respectively. Following mathematical induction and using (16) and (17), we are now able to find the iterative PGF of the nodes in the contention after the elapse of $t+1$ slots.

$$g_{c0}^{(m)}(z) = g_c^{(m)}\left((1-q_c^{(m)}) z_{fa}^{(m)}\right) , \tag{18}$$

where $c0$ means an additional bit b_{t+1}=0 is attached after c. And

$$\begin{aligned} g_{c1}^{(m)}(z) = \quad & g_c^{(m)}\left(q_c^{(m)} z + (1-q_c^{(m)}) z_{md}^{(m)}\right) \\ & - g_c^{(m)}\left(\left(1-q_c^{(m)}\right) z_{md}^{(m)}\right) , \end{aligned} \tag{19}$$

where $c1$ means an additional bit b_{t+1}=1 is attached after c. $q_c^{(m)}$ is the probability that, in slot $t+1$, nodes emit a carrier on the m-th channel, given the signaling pattern c in the first t slots, $g_c^{(m)}$ is the PGF of survivors, when the signaling pattern in the first t slots is c, and $g_{\varnothing}^{(m)} := g^{(m)}$. Hence, the PGF of the number of contenders on the m-th channel after k slots is $\sum_{c\in\mathcal{C}_k} g_c^{(m)}(z)$, where $\mathcal{C}_k$ denotes the set of all binary numbers of length k from the alphabet $\{0,1\}$. So the distribution of n nodes remain on the m-th channel is given by

$$p_n^{m-\text{th}} = \frac{1}{n!} \frac{d^n}{dz^n} \sum_{c\in\mathcal{C}_k} g_c^{(m)}(z)|_{z=0} \,, \tag{20}$$

where n denotes the number of survivors at the end of the contention. The success probability, which is defined as the probability that at the end of the contention only one survivor remains, is given as

$$\tau_{q^{(m)}} = \frac{d}{dz} \sum_{c\in\mathcal{C}_k} g_c^{(m)}(z)|_{z=0} \,. \tag{21}$$

Based on the selection of optimal energy detecting parameters λ and the probability distributions obtained by Algorithm 1, we can obtain the maximum success probability (5) of the sensing errors case.

VI. Numerical Results

In this section, we present numerical results to illustrate the performance of the proposed protocol. Throughout the simulation, we assume the number of nodes connected to the DC power line, N, is 50, and the shape parameter of the distribution in (1) is set to 0.6, unless specified otherwise. The reason behind choosing $\gamma = 0.6$ is that the system can perform well in both high and low traffic loads as shown in Fig. 7. Here, there are $N = 50$ nodes connected to the harness, and the system uses $M = 2$ channels and $k = 6$ slots to resolve the contention between nodes. It can be noted that the system with $\gamma = 0$ (uniform distribution) performs well when the number of contenders is large, whereas the system with $\gamma = 1$ gives a better performance when the number of contending nodes is small, and the system with $\gamma = 0.6$ provides a good performance in both cases. Our experiments confirm that $\gamma = 0.6$ provides a balanced performance for other configurations as well, i.e., different values of M and k.

Figs. 8 and 9 show the success probability and the system throughput as the number of channels varies between 2 and 8 for different number of contention slots, respectively. To evaluate the effects of the number of frequency channels and contention slots on the system throughput, we define a ratio between time constants in each transmission cycle as $r := \frac{\sigma_s}{\sigma_d} = \frac{\sigma_c}{\sigma_d}$, where σ_s, σ_c and σ_d are defined in (11). Here, we considered that $\sigma_s = \sigma_c$, however, the case of $\sigma_s \neq \sigma_c$ can be easily included in the numerical evaluations as well. Expectedly, as can be observed in Fig. 8, with an increasing number of contention slots or frequency channels, the success probability of the protocol increases. However, as the number of contention slots increases, the gain of using multiple frequency channels decreases, since the protocol is capable of resolving the contention on each channel with a high probability. In Fig. 9, we assume that the packet size is relatively large, and therefore $r = \frac{1}{60}$. Each point describes the expected throughput computed as $\sum_{n=2}^{N} p_N(n)\rho_1(n)$, and the maximum point along each curve is specified with a marker. We can observe that, as the number of contention slots increases, the maximum point along each curve moves to the left and thus, occurs at a smaller number of channels. It can also be seen that adding a channel to the system does not improve the system performance when number of contention slots used in the system is high. The reason behind this behavior is that the system with large k can handle a wide range of traffic loads, and therefore the success probability will not improve much by separating contenders across more channels. On the other hand, adding one more channel will increase the packet overhead and thus potentially degrade the system performance.

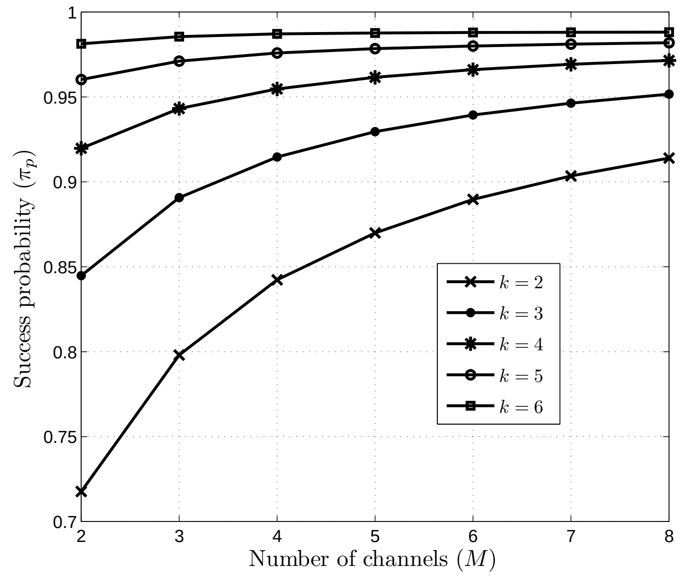


Fig. 8. Average success probability versus number of channels for different number of time slots (k), $N = 50$, $\gamma = 0.6$.

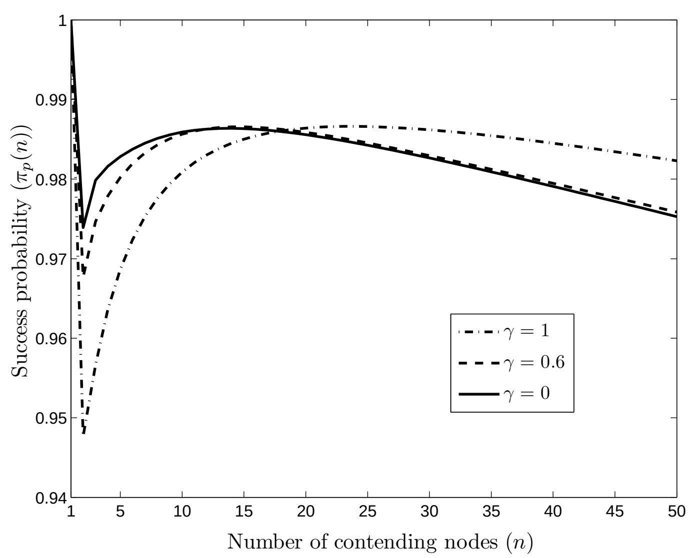


Fig. 7. Success probability versus number of contending nodes for different values of γ, $N = 50$, $k = 6$, $M = 2$.

Fig. 10 shows the average success probability of the system as a function of the network size. The protocol operational parameters (k, M) are set to the values giving the maximum throughput as shown in Fig. 9. It could be noticed that the system shows the least performance degradation when $k = 6$ and $M = 2$. The reason is that as we increase the number of contention slots in each channel, the collision resolution algorithm performed on each channel is more capable of resolving the contention in a wide range of traffic loads, and also less sensitive to the number of contenders compared to the channel selection algorithm.

In Fig. 11 and Fig. 12, we report the probability mass functions of the number of transmission cycles required to transmit the first and all packets, when there are 25 and 5 contenders, respectively. We assume there are $k = 4$ slots available on each channel to resolve the contention, and the system uses $M = 3$ channels according to Fig. 9, this configuration provides the highest throughput when $k = 4$. We

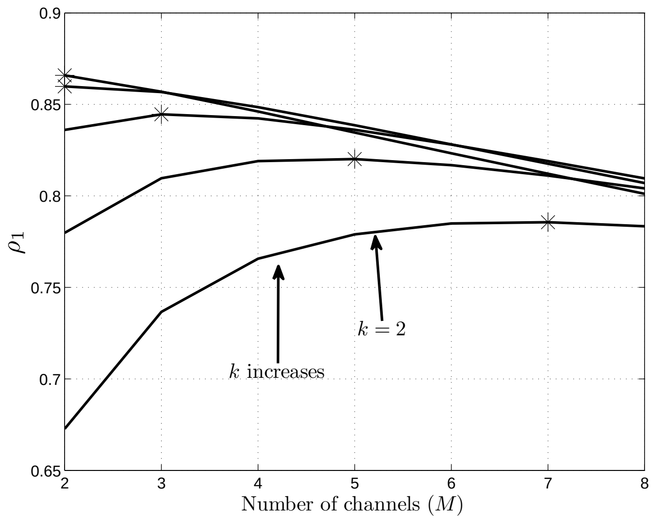


Fig. 9. ρ_1 versus number of channels for different number of time slots (k), $N = 50$, $\gamma = 0.6$.

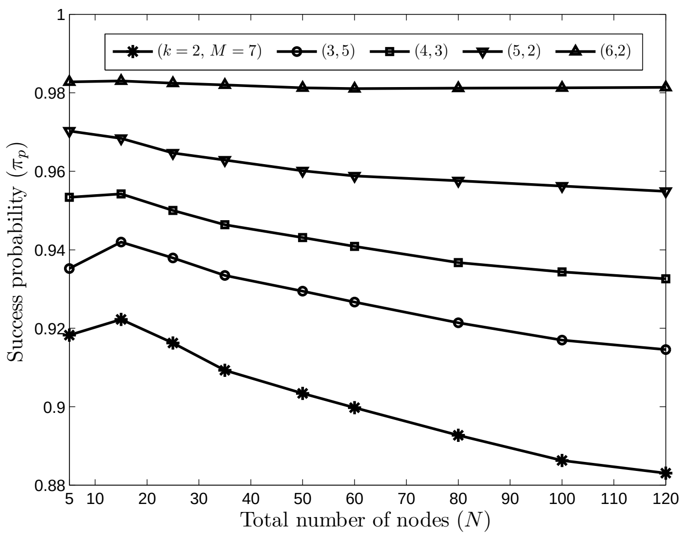
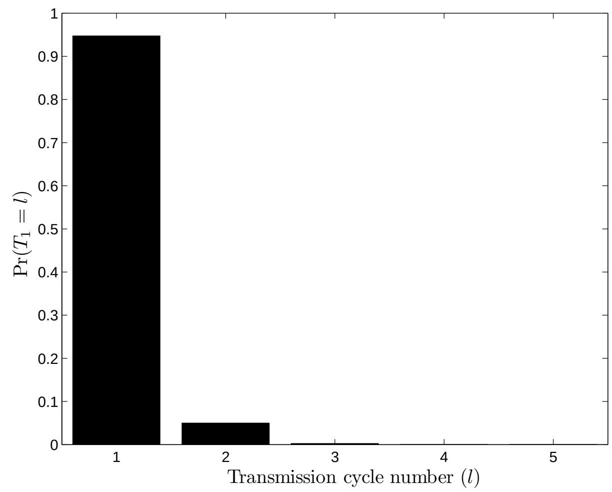
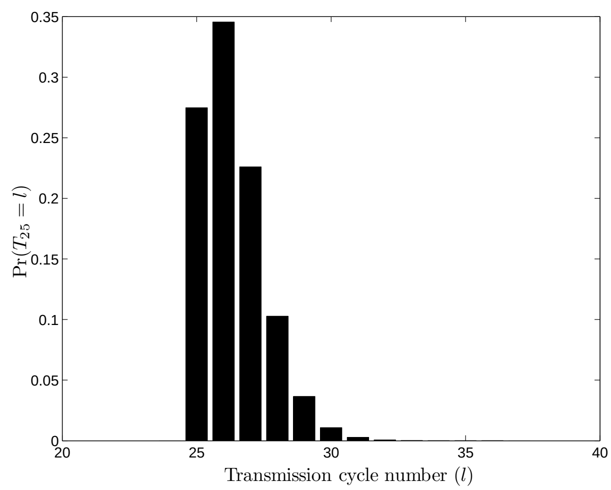


Fig. 10. The average success probability versus total number of nodes connected to the harness (N), $\gamma = 0.6$.



(a) first packet.



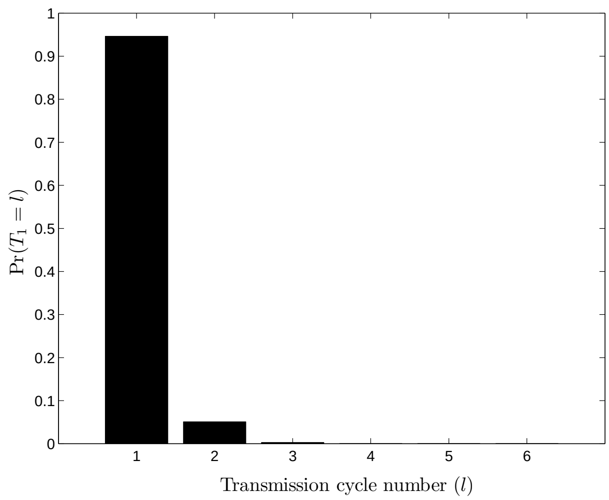
(b) all packets.

Fig. 11. Probability mass function of the number of transmission cycles required to transmit the first packet (a) all packets (b) when there are 25 contenders, $N = 50$, $\gamma = 0.6$, $k = 4$, $M = 3$.

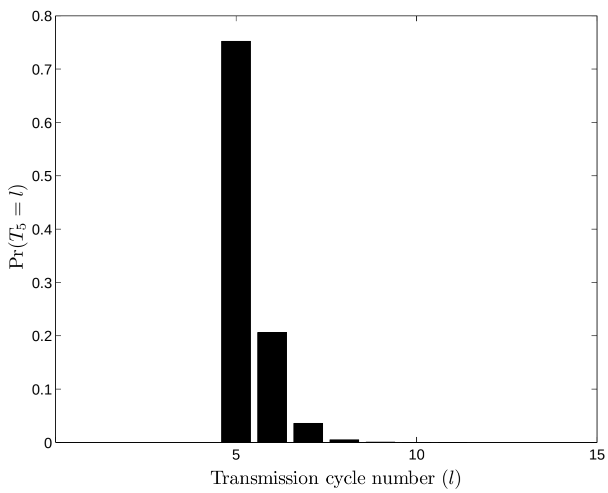
have plotted theses distributions by using (9), and the results obtained by solving the optimization problem given in (6). The figures show that the protocol delivers the packets with small latency and also scales well with respect to the number of contenders.

Fig. 13 gives a success probability comparison between our proposed MAC protocol and CDR [5], when the number of contending nodes varies between 2 and 50. To make a fair comparison, we note that adding one more channel or slot to our system increases the packet overhead by the same amount as adding one more slot to the CDR protocol. The number of channels, in our system, is fixed to 3. We would like to remark that the parameters used in our protocol are calculated by solving the optimization problem in (6) with the distribution in (1), when $N = 50$ and $\gamma = 0.6$, and thus the protocol does not need to know about the number of contenders. It can be observed that our protocol performs much better in all scenarios, and its performance deteriorates at a much lower rate compared to CDR as we increase the number of contending nodes. With the same assumption, Fig. 14 further shows the throughput ρ_1 comparison of the proposed solution and CDR. We also assume that the packet size is relatively large and with $r = \frac{1}{60}$. It is clear that the result is proportional to the probability result, which can be proved from (11).

According to (13) and (14), the sensing errors are directly related to the threshold λ of energy detector. The effect of λ on the average success probability is depicted in Fig. 15. We consider the scenario where $k = 6$ slots and $M = 2$ channels are used in the system as it provides a high throughput according to the Fig. 9. The values of SNRs are set between -5dB to 5dB, and are chosen randomly in each channel. Note that each point in the figure represents the average success probability as in (5), and is averaged over 1,000 runs. We



(a) first packet.



(b) all packets.

Fig. 12. Probability mass function of the number of transmission cycles needed to transmit the first packet (a) all packets (b) when there are 5 contenders, $N = 50$, $\gamma = 0.6$, $k = 4$, $M = 3$.

also assume that the sensing module takes 20 samples to determine the presence or absence of the carrier. It is clear that the decision of threshold λ on each channel plays a critical role on the performance of overall success probability and there is an optimal selections of λ which can maximize the success probability. Since the main focus of the paper is on the maximization of π_p, we will evaluate the maximum success probability (6) that can be achieved by optimally selecting system parameters in the following.

We design a robust system by considering the carrier sensing errors. We plot the results for three cases corresponding to $r = \frac{1}{60}, \frac{1}{20}, \frac{3}{20}$. Note that in all cases the packet length is fixed, and instead the number of samples taken from the received signal changes. There are $M = 2$ channels available in the system for contention, and assume the SNRs correspond to these channels are 5dB (good channel) and 0dB (bad channel). Figs. 16-17 show the systems where the detector operating point is optimized on each channel with respect to the physical layer characteristics, and correspond to the cases where the good channel is indexed as the first channel and vice versa, respectively. We can make the following observation. The success probability decreases when the bad channel is indexed 1. This happens since, according to (7), the receiver will receive the packet from the low-indexed channels with high probability, and a low SNR on the selected channel can degrade the performance of the collision resolution algorithm performed on that channel. Hence, we can shuffle the order of the channels in each transmission cycle to reduce the impact of the noise and fading on the MAC protocol performance. Moreover, we obtain additional results for $M > 2$ and with equal channel quality. Fig. 18 illustrates the success probability for $M = 3$ when SNRs of all channels are equally good (5dB), and shows that all channels can achieve decent performance when sampling rates (r) are closed. Fig. 19 shows the result for $M = 5$ when SNRs of all channels are equally bad (0dB). It is clear that the performance is deteriorated with the poor channel condition, however, the scheme with a larger sampling rate is robust to compact carrier sensing errors.

VII. CONCLUSIONS

We have introduced a random access MAC protocol based on the combination of time and frequency multiplexing. Nodes in the contention randomly select a frequency channel to perform channel contention in a number of slots. After that, the receiver samples the signal level on each frequency channel and stops on the first non-idle channel to receive the packet. We mathematically analyzed the performance of the proposed MAC protocol under both perfect and imperfect sensing. With numerical evaluations, we have verified our analysis and demonstrated the effectiveness of our MAC protocol. Our results show that the system demonstrates a good performance in terms of collision probability, system throughput, and delay.

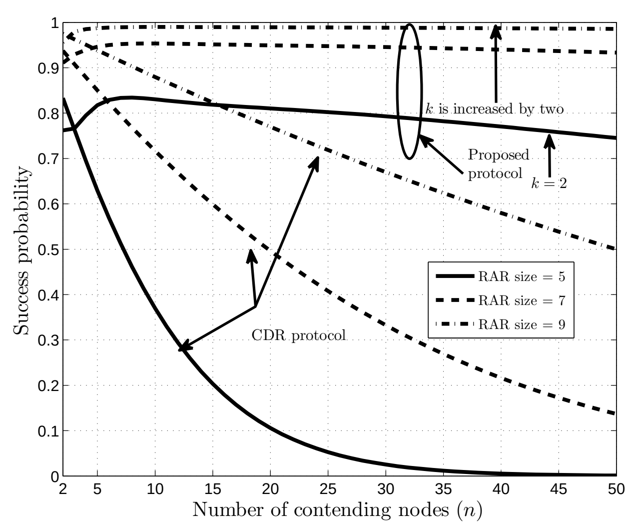


Fig. 13. Success probability of the proposed protocol and CDR versus number of contending nodes, $M = 3$, $N = 50$, $\gamma = 0.6$.

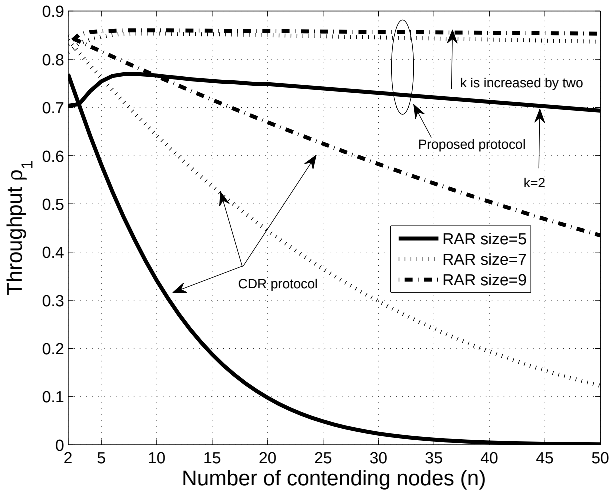


Fig. 14. Throughput ρ_1 of the proposed protocol and CDR versus number of contending nodes, $M = 3$, $N = 50$, $\gamma = 0.6$.

In this work, we have also considered that the system is not free from carrier sensing errors, and we have observed that a great care must be taken into account when designing such a system.

In the future work, we will promote the two-dimensional MAC protocol into a more practical implementation. Specifically, a live demonstration has been built based on a network simulator [37]. Also, we intent to incorporate the proposed method with existing PLC solution, i.e., HomePlug, and further extend its usability and compatibly with home automation and smart grid.

Acknowledgments

This work was supported by a grant from AUTO21 under the Canadian Network of Centres of Excellence Program.

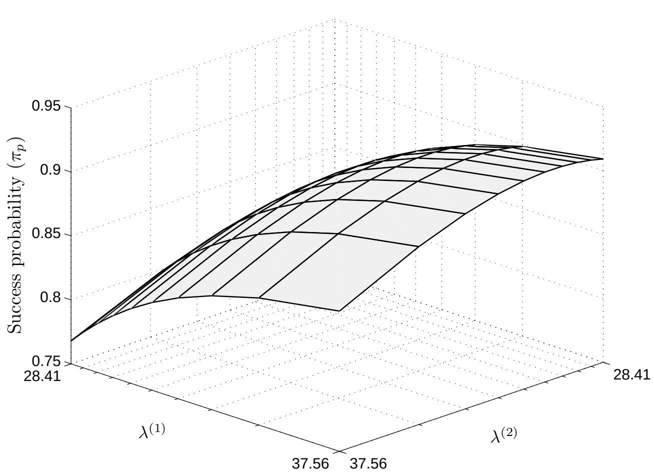


Fig. 15. The average success probability versus threshold λ of the energy detector, $N = 50$, $\gamma = 0.6$, $k = 6$, $M = 2$, $u = 10$.

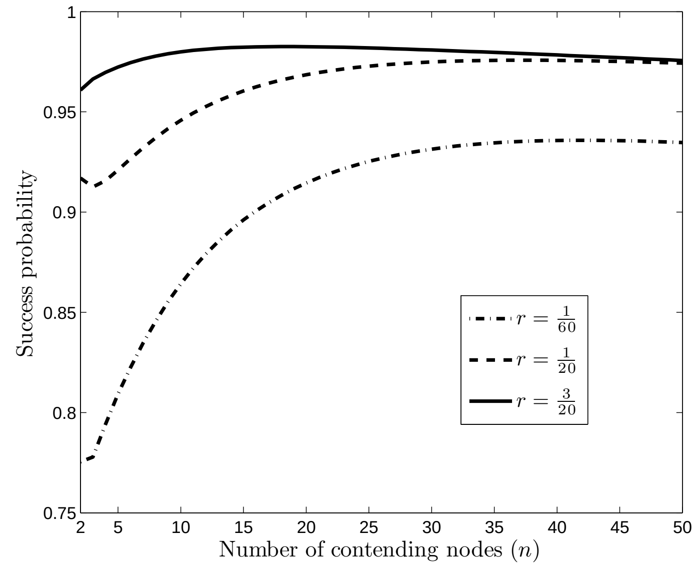


Fig. 16. Success probability versus number of contending nodes for multiple values of r, where good channel is indexed 1, $k = 6$, $M = 2$, $N = 50$, $\gamma = 0.6$.

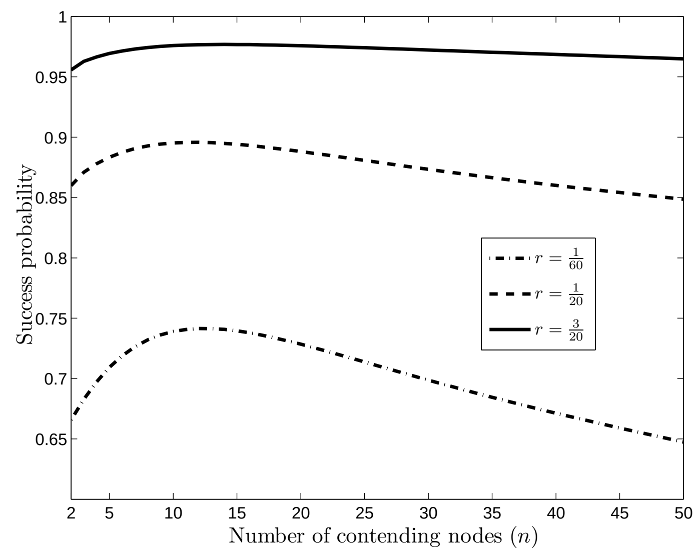


Fig. 17. Success probability versus number of contending nodes for multiple values of r, where bad channel is indexed 1, $k = 6$, $M = 2$, $N = 50$, $\gamma = 0.6$.

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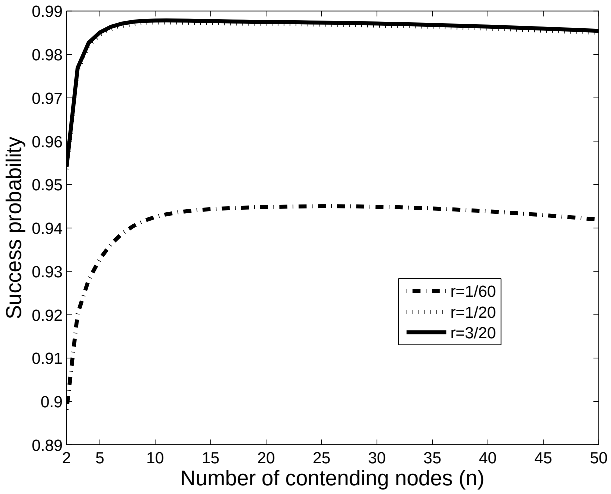

Fig. 18. Success probability versus number of contending nodes for multiple values of r, where channels are equally good, $k = 6$, $M = 3$, $N = 50$, $\gamma = 0.6$.

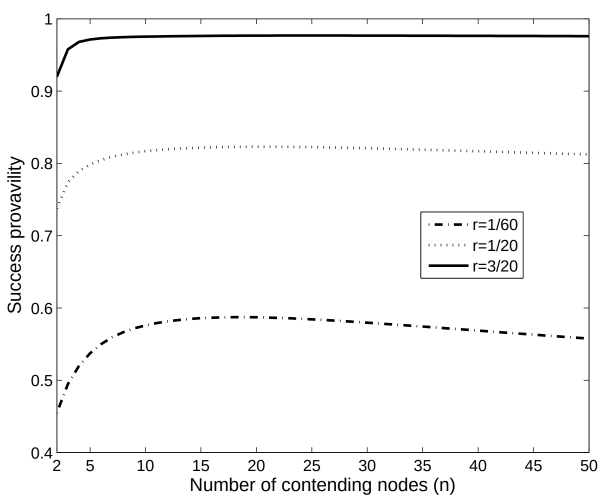

Fig. 19. Success probability versus number of contending nodes for multiple values of r, where channels are equally bad, $k = 6$, $M = 5$, $N = 50$, $\gamma = 0.6$.

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