Throughput, Stability and Fairness of Carrier-Sense Multiple Access with Cooperative Diversity

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Abstract

Cooperative diversity has been identified as a potential candidate for boosting the physical (PHY) layer performance of future wireless networks. However, several issues remain open today in the design of an appropriate medium access control (MAC) layer for this type of system. This paper attempts to partially fill this gap by addressing the MAC-PHY cross-layer design of a class of carrier-sense multiple access protocols where collision-free transmissions are assisted by the potential cooperative retransmission of the remaining silent terminals in the network. Unlike previous works, the analysis is focused on full asymmetrical settings, where terminals experience different channel and queuing statistics. To achieve this goal, a packet reception model is here proposed for cooperative schemes where the relaying phase is activated only when the reception of previous (re)transmissions has failed. Closed-form expressions of correct reception probability are derived for Rayleigh fading channels assuming that correct reception occurs only when the instantaneous signal-to-noise ratio (SNR) exceeds a reception threshold. This reception model allows for a MAC-layer design aware of PHY-layer information, and vice versa, PHY-layer enhancement and activation using MAC-layer information. The boundary of the throughput region (i.e., the set of all achievable throughput values) is derived in a parametric closed-form expression using a multi-objective optimization approach. A method for deriving a non-parametric form was further proposed, which allows for a geometric interpretation of the two-user case. Stability features such as backlog user distribution and backlog delay are evaluated by using a novel Markov model for asymmetrical systems. Fairness is evaluated by means of the Gini index, which is a metric commonly used in the field of economics to measure income inequality. The protocol is shown to outperform its non-cooperative counterparts under diverse network conditions that are here discussed.

Keywords

Cooperative Diversity; Random Access; Throughput Region; Stability; Markov Model

Introduction

Cooperative Diversity vs. Distributed Antenna Systems

Future wireless networks will make use of advanced signal processing tools to cope more efficiently with harsh propagation conditions and increasing bandwidth demands. In particular, MIMO (multiple-input multiple-output) technology has received a lot of attention in recent years thanks to its ability to increase spectral efficiency without the need of additional bandwidth or power budget (Goldsmith, 2003). However, MIMO systems suffer from the problem of high correlation between the signals of the antenna elements, mainly because of space/size limitations of terminals and base stations (BSs) (Choi, 2007).

A solution to the correlation problem can be found in the areas of distributed antenna systems (DAS) and cooperative relaying diversity. In both types of system, the problem of signal correlation is minimized by distributing the antenna elements over a relatively large geographical area. They differ from each other on how the distributed elements are interconnected to the BS (where all signals are processed). In DAS, this connection is achieved via coaxial cables or optical links (Choi, 2007). By contrast, cooperative systems reuse the same bandwidth of the user-BS wireless communication link (Chen, 2008; Zho, 2010). While this feature can considerably reduce spectral efficiency of cooperative schemes, it avoids the fixed infrastructure of DAS, thereby reducing costs and facilitating deployment. Additionally, it allows terminals to act as mobile relays, thereby opening a wide range of mobile cooperative schemes. Cooperative diversity with mobile relays has thus become an important topic in recent years (Liu, 2006).

Open issues and Previous Works

Cooperative relaying diversity has been shown to provide considerable gains at the physical layer (PHY) (Chen, 2008). However, several issues remain open in the design of a medium access control (MAC) layer suitable for cooperative schemes, particularly in the field of random access (Scaglione, 2006). One of the first approaches in this area was the work in (Ribeiro, 2008),(Ribeiro, 2007), which showed that the throughput of cooperative random access with symmetrical users (i.e., statistically identical) asymptotically achieved the performance of conventional non-cooperative protocols in Gaussian channels. In recent years, however, it has been observed that for an appropriate design of cooperative systems, more realistic asymmetrical models and MAC-PHY cross-layer principles are required (Scaglione, 2006). An example of this cross-layer approach was the work in (Dong, 2008), which proposed a cooperative random access protocol, where collisions were resolved by requesting as many cooperative retransmissions as necessary to recover the contending signals via source separation. PHY-layer diversity was explicitly created by MAC-layer requests. This scheme is the cooperative version of the retransmission diversity algorithm previously proposed in (Tsatsanis, 2000). A unified framework for cross-layer design in cooperative networks has been described in (Chen, 2008), and a two-transmitter two-receiver cooperative cross-layer algorithm has been proposed in (Zhou, 2010). The work in (Samano-Robles, 2008) has addressed the analysis of a symmetrical ALOHA protocol where collision-free transmissions were assisted by cooperative diversity. To facilitate analysis, a reception model was proposed for a cooperative PHY-layer where the relaying phases were activated only when the reception of previous (re)transmissions has failed. This approach was found optimum for systems with half duplex constraints. The model, however, did not consider explicit channel statistics, while it also ignored the dependency between consecutive retransmissions that arises in systems with cooperative activation based on error detection.

Paper Contributions and Organization

To address some of the issues previously described, this paper proposes the MAC-PHY cross-layer design and optimization of a class of carrier-sense multiple access protocols where collision-free transmissions are assisted by the potential cooperative retransmissions of silent terminals in the network. The relaying protocol used is decode-and-forward (DF). The focus is on asymmetrical scenarios, where users experience different channel and queuing statistics. The paper proposes an enhanced packet reception model which can be easily used in MAC layer design and which mimics more accurately a cooperative and adaptive PHY-layer. This reception model, originally developed in (Samano-Robles, 2010) and adapted here to environments with mobile relays, assumes that correct reception occurs whenever the signal-to-noise ratio (SNR) exceeds a reception threshold. Furthermore, unlike previous approaches, the model considers the statistical dependency between consecutive retransmissions in systems where relaying phases are requested only when the reception in previous phases has failed. The main figure of merit is the throughput region, which can be considered as the set of all achievable user throughput values. A multi-objective optimization approach is proposed to derive the boundaries/envelope of the throughput region. A closed-form parametric expression of the envelope, which is also the Pareto optimal front curve, is derived for an arbitrary number of users. A method for obtaining a non-parametric form is also presented, which allows for an interesting geometric interpretation of the two-user case. Stability features are investigated by using a Markov model specially adapted for asymmetrical settings. Fairness is evaluated by means of the Gini index, which is commonly used in the field of economics to measure income inequality. The results indicate that carrier-sensing and cooperative diversity increase the throughput region, as well as stability and fairness metrics of non-cooperative algorithms under diverse network conditions that are further discussed in the paper. The results show the advantages of cross-layer design in cooperative systems.

The organization of this paper is as follows. Section II describes the proposed protocol. Section III describes the reception model. Section IV provides a parametric expression for the boundary of the throughput region. Section V provides a method for obtaining a non-parametric form, as well as a geometrical interpretation of the two-user case. Section VI describes the Markov model and other metrics for stability analysis. Section VII presents some performance results, and finally Section VIII presents the conclusions of the paper.

System Model and Protocol Description

Consider the slotted wireless random access network depicted in Fig. 1 with one base station (BS) and J user terminals. Each user j has a buffer that always has packets ready to be transmitted (full queue or dominant system model). All channels are independently and Rayleigh distributed with parameter σ_j for the user-BS link, and with parameter $\sigma_j^{(k)}$ for the link between user j and user k. Users are allowed to cooperate with each other by relaying, if necessary, their decoded signals towards the BS, where all received copies are conveniently combined. Since cooperation in half duplex systems requires more than one phase or time-slot, (re)transmissions will be arranged in periods or epoch-slots with a variable length (in time-slots) denoted by the random variable l. At the beginning of an epoch-slot, each user senses the channel, and in case of sensing it as idle then the user starts a packet random transmission process. The packet length will be fixed to L time-slots or packet-units. This means that the sensing operation is performed L times along the duration of a transmission. All packet collisions are assumed to represent the loss of all the transmitted information. However, whenever a collision-free transmission occurs, then all the silent terminals and the BS will attempt to decode the transmission. The binary random variable $t_{j,n}$ will denote whether the packet of user j (collision-free) is correctly decoded by the BS in the nth time-slot of an epoch (i.e., $t_{j,n}$=1) or not ($t_{j,n}$=0). Similarly, the binary random variable $t_j^{(k)}$ will denote whether the packet of user j is correctly decoded by the kth terminal ($t_j^{(k)}$=1) or not ($t_j^{(k)}$=0, $j \neq k$). If the BS finds the packet as erroneous then it requests its retransmission from another terminal via an ideal feedback channel. This feedback channel has four possible outcomes '*0/1/e/r*', which indicate, respectively, *idle slot* ('*0*'), *correct transmission* ('*1*'), *collision* ('*e*'), and *retransmission request* ('*r*'). If the feedback is '*r*' then all the remaining silent terminals with a correct version of the packet proceed to relay a copy in the next time-slot with probability p_R. The BS stores all the received copies and uses maximum ratio combining (MRC) with a maximum of M branches (which account for the initial transmission plus the potential retransmissions) to improve reception. Each retransmission is requested if the reception in previous and current transmissions has failed.

Fig. 1 shows an example with three active epochs: the first epoch is collision-free with one cooperative retransmission. The second epoch is also collision-free but without cooperation, while the third one is an epoch with collision. The idle slots have a length of one time-slot.

Two different models are used for the analysis of the protocol: a Bernoulli transmission model, which facilitates derivations, and a Markov model for the backlog states, which is useful for stability analysis.

Bernoulli Transmission Model

In the Bernoulli transmission model, all packets either backlogged[1] or new incoming will be treated equally. Therefore, at the beginning of every time-slot each user j will be assumed to attempt a packet transmission controlled by a Bernoulli random experiment with parameter p_j, which is also the transmission probability. The Bernoulli transmission model facilitates analytic derivations. However, since backlog and incoming streams are not differentiated, it is not possible to evaluate in detail the dynamics and stability properties of the protocol.

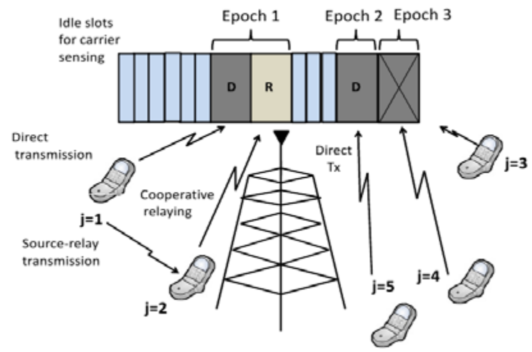

FIG. 1 RANDOM ACCESS NETWORK ASSISTED BY CARRIER-SENSING AND BY COOPERATIVE DIVERSITY

Backlog State Model

To overcome the issues of the Bernoulli transmission model, we reformulate the operation of the protocol so that the incoming and backlog traffic are scheduled in different manner by each terminal. In this approach, each user j is assumed to be in two possible states: idle (with probability $p_{i,j}$), or backlog (with probability $p_{b,j}$). In the idle state, each user j attempts the transmission

1 A user is assumed to be in the backlog state when having previously transmitted a packet, it was lost in a collision and needs to be retransmitted.

of a new packet with probability $p_{a,j}$. In the case of a collision (and upon the reception of the feedback from the BS confirming the collision event) each contending user is driven into the backlog state. In this backlog state, a user will attempt the retransmission of the packet previously lost with a backlog retransmission probability $p_{r,j}$. While a terminal is in the backlog state, no new packets from its queue are allowed to be transmitted.

Packet Reception Model

This section presents the reception model for cooperative and non-cooperative transmissions in the absence of collision. Consider that the instantaneous post-MRC SNR of user j during the nth slot of an epoch is denoted by $\Gamma_{j,n}$. The correct reception probability of a packet of user j during the nth slot, denoted by $q_{j,n}$, is given by the probability that the instantaneous SNR surpasses a reception threshold β:

$$q_{j,n} = \Pr\{t_{j,n}=1\} = \Pr\{\Gamma_{j,n}>\beta\}. \quad (1)$$

Consider that the instantaneous SNR of a transmission of user j experienced by the kth terminal that will act potentially as relay is denoted by $\Gamma_j^{(k)}$. The correct reception probability of a packet of user j at relay k, denoted by $q_j^{(k)}$, is defined as:

$$q_j^{(k)} = \Pr\{t_j^{(k)}=1\} = \Pr\{\Gamma_j^{(k)}>\beta\} . \quad (2)$$

Since all channels are Rayleigh distributed, then the SNRs both at the destination and at the potential relays during the first time-slot of an epoch are exponentially distributed. The reception probabilities in (1) (for n=1) and in (2) are thus given by the complementary cumulative distribution function (CCDF) of the exponential distribution (Proakis, 2001):

$$q_{j,1} = \exp(-\beta/\gamma_{j,1}) \quad \text{and} \quad q_j^{(k)} = \exp(-\beta/\gamma_j^{(k)}), \quad (3)$$

where $\gamma_{j,1} = E[\Gamma_{j,1}] = (\sigma_j)^2$, $\gamma_j^{(k)} = E[\Gamma_j^{(k)}] = (\sigma_j^{(k)})^2$, and $E[.]$ is the statistical average operator. Let us denote the pre-MRC processing SNR of user j during the nth time-slot of an epoch by $\Upsilon_{j,n}$. Since $\Upsilon_{j,n}$ is exponentially distributed (due to the Rayleigh channel assumption), then its probability density (PDF) and characteristic functions (CF) are given, respectively, by (Proakis, 2001)::

$$f_{\Upsilon j,n}(\Upsilon_{j,n}) = \exp(-\Upsilon_{j,n}/\upsilon_j)/\alpha_j \quad \text{and} \quad \Psi_{\Upsilon j,n}(i\omega) = (1-i\omega\alpha_j)^{-1} \quad (4)$$

where $i = \sqrt{(-1)}$, $\upsilon_j = E[\Upsilon_{j,n}] = \Sigma_{k\varepsilon R j}\, \gamma_{j,1}$, and R_j is the set of mobile relay nodes cooperating with user j. By using MRC, the total SNR (post-MRC) is the summation of the SNRs (pre-MRC) of all transmissions:

$$\Gamma_{j,n} = \Gamma_{j,1} + \textstyle\sum^{n}_{m=2} \Upsilon_{j,m} . \quad (5)$$

Since all channels are statistically independent, the CF of $\Gamma_{j,n}$ is given by the product of the CFs of each SNR component (Proakis,2001):

$$\Psi_{\Gamma j,n}\,(i\omega) = (1-i\omega\gamma_{j,1})^{-1}(1-i\omega\upsilon_j)^{1-n} . \quad (6)$$

By using partial fraction expansion (PFE) (6) becomes:

$$\Psi_{\Gamma j,n}(i\omega) = \Psi g(i\omega)+\Psi p(i\omega) , \quad (7)$$

where (see details in Appendix): $\Psi g(i\omega)=A_j(1-i\omega\gamma_{j,1})^{-1}$, $A_j=(1-\upsilon_j/\gamma_{j,1})^{1-n}$, $\Psi p(i\omega) = \sum^{n-1}_{m=1}B_{j,m}(1-i\omega\upsilon_j)^m$, and $B_{j,m} = (-\upsilon_j/\gamma_{j,1})(1-\upsilon_j/\gamma_{j,1})^{m-n}$. The back-transform of (7) yields the following CDF:

$$F_{\Gamma j,n}\,(\Gamma_{j,n}) = 1-G(\Gamma_{j,n})- P\,(\Gamma_{j,n}) , \quad (8)$$

where $G(\Gamma_{j,n}) = A_{j,n}\exp(-\Gamma_{j,n}/\gamma_{j,1})$ and $P(\Gamma_{j,n}) = \exp(-\Gamma_{j,n}/\upsilon_j)\sum^{n-1}_{m=1}B_{j,m}\sum^{m-1}_{k=1}(1/k!)(\Gamma_{j,n}/\upsilon_j)^k$. Since relaying phases are activated when reception in previous transmissions has failed, the relevant distributions to be obtained should be the truncated versions of the previous expressions. This means that all probabilities should consider that the combined SNR in previous time-slots did not surpass the reception threshold. Consider the truncated version of $f_{\Gamma j,n-1}\,(\Gamma_{j,n-1})$:

$$f_{\Gamma j,n-1\mid\Gamma j,n-1<\beta}(\Gamma_{j,n-1}) = f_{\Gamma j,n-1}(\Gamma_{j,n-1}) \,/\, F_{\Gamma j,n-1}(\beta), \qquad \Gamma_{j,n-1}<\beta . \quad (9)$$

The CF of this distribution can be expressed as:

$$\Psi_{\Gamma j,n-1\mid\Gamma j,n-1<\beta}\,(i\omega) = \Psi g(i\omega)(1-G\,[\beta(1-i\omega\gamma_{j,1}])/F_{\Gamma j,n-1}\,(\beta)$$
$$+\Psi p(i\omega)(1-P[\beta(1-i\omega\gamma_{j,1}])/F_{\Gamma j,n-1}\,(\beta) . \quad (10)$$

By using the properties of the Fourier transform, it can be observed that the terms $G[\beta(1-i\omega\gamma_{j,1}]$ and $P[\beta(1-i\omega\gamma_{j,1}]$ are only relevant for values of $\Gamma_{j,n-1}$ larger than β in the back-transform domain. Since we are interested only in values smaller than β, these terms will not be considered in subsequent calculations. Therefore, the previous expression simplifies to:

$$\Psi_{\Gamma j,n-1\mid\Gamma j,n-1<\beta}\,(i\omega) = \Psi_{\Gamma j,n-1}\,(i\omega)/F_{\Gamma j,n-1}\,(\beta), \qquad \Gamma_{j,n-1}<\beta. \quad (11)$$

Let us consider the maximum ratio combining of this truncated distribution of n-1 transmissions with the nth transmission:

$$\Gamma_{j,n} = \Gamma_{j,n-1} + \Upsilon_{j,n} \ , \quad \Gamma_{j,n-1}<\beta , \quad (12)$$

whose characteristic function, considering (4), is given by:

$$\Psi_{\Gamma j,n\mid\Gamma j,n-1<\beta}\,(i\omega) = \Psi_{\Gamma j,n\mid\Gamma j,n-1<\beta}\,(i\omega)\,(1-i\omega\upsilon_j)^{-1} . \quad (13)$$

The back-transform of the CF in (13) yields the following cumulative distribution function (CDF):

$$F_{\Gamma j,n\mid\Gamma j,n-1<\beta}\,(\Gamma_{j,n}) = F_{\Gamma j,n}\,(\gamma_{j,n})/\,F_{\Gamma j,n-1}\,(\beta) , \quad \Gamma_{j,n-1}<\beta . \quad (14)$$

The reception probability during the nth time slot of an epoch given an incorrect packet reception in the previous n-1 transmissions is thus given by:

$$q_{j,n\mid t_{j,n-1}=0} = 1\text{-}F_{\Gamma_{j,n}\mid\Gamma_{j,n-1}<\beta}(\beta)\ . \qquad (15)$$

Throughput Region (optimization)

The main performance metric to be used is throughput, which can be defined in general as the long-term ratio of the total number of correctly transmitted packet-units to the total number of time-slots used in the measurement. This can be proved, in our setting, to be equivalent to the ratio of the average number of correctly received packet-units per epoch-slot to the average length of an epoch-slot ($E[l]$). Considering that collisions yield the loss of all contending packets, then a transmission of user j is free of collision with probability $p_j\prod_{k\neq j}(1\text{-}p_k)$. In addition, consider that $p_{s,j}$ is the correct packet reception of user j given that its transmission is free of collision and that cooperation is potentially used. The throughput can thus be expressed as:

$$T_j = P_{s,j}/E[l] = Lp_{s,j}p_j\prod_{k\neq j}(1\text{-}p_k)/E[l], \qquad (16)$$

where the correct packet reception of user j in absence of collision can be obtained by adding the contributions from all M possible cooperative stages:

$$p_{s,j} = q_{j,1}+\sum\nolimits^{M}_{n=2} q_{j,n\mid t_{j,n-1}=0}\prod\nolimits^{n-1}_{m=1}(1\text{-}\ q_{j,m\mid t_{j,m-1}=0}), \qquad (17)$$

where $q_{j,m\mid t_{j,m-1}=0} = q_{j,1}$ when m=1. The average length of an epoch-slot can be obtained by considering all contributions of idle and busy epoch-slots: one time slot with probability $\prod_k(1\text{-}p_k)$, at least L time slots with probability $1\text{-}\prod_k(1\text{-}p_k)$, and more than L time-slots with probability $\sum_j p_j\prod_{k\neq j}(1\text{-}p_k)$ weighted by $E[l_{c,j}]$, which is the average number of cooperative retransmissions for user j once a cooperative phase has been activated. The average length of an epoch can thus be written as:

$$E[l] = \sum\nolimits_j LE[l_{c,j}]p_j\prod_{k\neq j}(1\text{-}p_k)+L+(1\text{-}L)\prod_k(1\text{-}p_k), \qquad (18)$$

where $E[l_{c,j}]$ is given by the summation of all contributions of the M potential cooperative stages:

$$E[l_{c,j}] = \sum\nolimits^{M}_{n=2}(n\text{-}1)\ q_{j,n\mid t_{j,n-1}=0}\prod\nolimits^{n-1}_{m=1}(1\text{-}q_{j,m\mid t_{j,m-1}=0})\ . \qquad (19)$$

Let us now define the concept of throughput region. For this purpose, let $\mathbf{T} = [T_1, \ldots, T_J]^T$ be the vector of stacked throughput values of all users, and $\mathbf{p} = [p_1, \ldots, p_J]^T$ the vector of stacked transmission probabilities. The throughput region C_T is the union over all possible realizations of transmission probabilities (Luo, 2006):

$$C_T = \{\mathbf{T} \mid T_j = T_j(\mathbf{p}),\ 0<p_j<1\}, \qquad (20)$$

which can be simply considered as the region of all achievable throughput values. The throughput region is the main performance metric used in the analysis of random access in asymmetrical settings (Luo, 2006).

To derive the boundaries of the throughput region, a multi-objective optimization method is here proposed, where all T_j's can be simultaneously optimized:

$$\mathbf{p}_{\mathbf{opt}} = \mathrm{argmax}_{\mathbf{p}}\,[T_1, \ldots, T_J]\ . \qquad (21)$$

Since this vector optimization usually lacks of a unique solution (Boyd, 2004), the concept of Pareto optimality is commonly employed. A Pareto optimal point is such a solution that is at least optimum for one or more of the elements of the vector objective function $\mathbf{T}$. The multi-objective optimization problem can be rewritten as a single objective optimization problem using the method of scalarization [15]:

$$\mathbf{p}_{\mathbf{opt}} = \mathrm{argmax}_{\mathbf{p}}\sum\nolimits_j \mu_j T_j\,, \qquad (22)$$

where μ_j is the relative weight given to the jth objective function. Diferentiating the objective function in (22) we obtain a set of equations given by $\sum_k \mu_k\,\partial T_k/\partial p_j = 0$, j,k =1..,J. The solution of this set of linear equations which is independent from the values of the weighting factors μ_k can be easily proved, in our context, to be equivalent to setting the following Jacobian determinant to zero (Samano-Robles, 2009) (Abramson, 1977):

$$\mid\mathbf{J}\mid = 0\,, \qquad (23)$$

where $\mid.\mid$ denotes the determinant operator and $\mathbf{J}$ is the Jacobian matrix with elements given by $J_{k,j}=\partial T_k/\partial p_j$. For convenience, let us express the first-order derivative of $p_{s,k}$ with respect to p_j as follows:

$$\partial p_{s,k}/\partial p_j = Lp_{s,j}\prod_{m\neq j}(1\text{-}p_m)\,,\quad k=j,\quad \text{and}$$

$$\partial p_{s,k}/\partial p_j = \text{-}Lp_{s,k}\,p_k\prod_{m\neq j,k}(1\text{-}p_m)\quad k\neq j. \qquad (24)$$

Using the properties of determinants we can write a modified version of $J_{k,j}$ as follows:

$$(E[l]^2/P_{s,k})\partial T_k/\partial p_j = (1/P_{s,k})(E[l]\ \partial p_{s,k}/\partial p_j\text{-}\ P_{s,k}\partial E[l]/\partial p_j)\ . \qquad (25)$$

By substituting (24) in (25) we obtain:

$$(E[l]^2/P_{s,k})\partial T_k/\partial p_j = E[l]/p_j\ \text{-}\partial E[l]/\partial p_j\ ,\qquad k=j,$$

$$(E[l]^2/P_{s,k})\partial T_k/\partial p_j = \text{-}[E[l]/(1\text{-}p_j)]\ \text{-}\partial E[l]/\partial p_j\ ,\qquad k\neq j \quad (26)$$

If we use this last expression in (23) then it is possible to simplify it by using the properties of the determinants or by following the steps described by (Abramson, 1977) or in the Appendix of (Samano-Robles, 2009), which yields:

$$\sum_j \{ [E[l]/(1-p_j) - \partial E[l]/\partial p_j] / [1/(1-p_j)+1/p_j)] \} = E[l], \quad (27)$$

which can be further simplified to:

$$\sum_j [p_j E[l] + (1-p_j) p_j \partial E[l]/\partial p_j] = E[l]. \quad (28)$$

By substituting (18) for $E[l]$ and its partial derivative $\partial E[l]/\partial p_j$ in (28) we obtain the final expression for the optimum transmission probabilities:

$$\sum_j L p_j = L + (1-L) \prod_k (1-p_k) \ . \quad (29)$$

This expression together with the expression for the throughput of the different users in (16) characterizes the boundary of the throughput region in a parametric form, which means that the expression depends on the transmission probabilities. The following section provides a method for obtaining generalized non-parametric expressions by dropping the dependency on the transmission probabilities.

Throughput Region: Non-parametric form

Let us define the following normalized throughput per terminal:

$$\underline{T}_j = T_j / p_{s,j} \ . \quad (30)$$

We now obtain the ratio of two arbitrary throughput expressions of (30) as follows:

$$\underline{T}_j / \underline{T}_k = p_j (1-p_k) / [p_k (1-p_j)] \ . \quad (31)$$

which can be rearranged as follows:

$$p_j \underline{T}_k - p_k \underline{T}_j + (\underline{T}_j - \underline{T}_k) p_j p_k = 0. \quad (32)$$

We now obtain the product term $p_j p_k$ from the previous expression:

$$p_j p_k \underline{T}_{kj} = p_j \underline{T}_k - p_k \underline{T}_j. \quad (33)$$

where $\underline{T}_{kj} = \underline{T}_k - \underline{T}_j$. A modified version of (33) is as follows:

$$(1-p_j)(1-p_k) = [(1-p_k) \underline{T}_k - (1-p_j) \underline{T}_j] / \underline{T}_{kj} \quad (34)$$

Alternatively, this expression can be rearranged as follows: $(1-p_j)(1-p_k) = 1-(p_k \underline{T}_k - p_j \underline{T}_j)/\underline{T}_{kj}$. Another useful modification is the following: $p_j (1-p_k) = \underline{T}_j (p_k - p_j)/\underline{T}_{kj}$. The relevance of the expression in (34) is that it provides a method for transforming probability product terms into linear combinations of transmission probabilities. For example, by substituting (34) recursively in the term $\prod_k (1-p_k)$ we obtain:

$$\prod_j (1-p_j) = \sum_j (-1)^{J-j} (1-p_j) (\underline{T}_j)^{J-1} \prod_{\theta_2; j \ni \theta_2} \underline{T}_{\theta_2} / \prod_{\theta_2} \underline{T}_{\theta_2} \quad (35)$$

where θ_2 indicates an arbitrary set of two users, $\ni$ denotes the '*not belong*' operator, and $\prod_{\theta_2} \underline{T}_{\theta_2}$ indicates the product of differential throughput functions ($\underline{T}_{kj}$) over all the possible combinations of two different users (k and j). Using a similar approach, the following product term can be written as

$$p_k \prod_{j \neq k} (1-p_j) = \sum_j (-1)^{J-j} (1-p_j) \underline{T}_k (\underline{T}_j)^{J-2} \prod_{\theta_2; j \ni \theta_2} \underline{T}_{\theta_2} / \prod_{\theta_2} T_{\theta_2} \quad (36)$$

By substituting (35) in (29) we obtain the following linear expression:

$$\sum_j \lambda_j p_j = \lambda_0 \quad (37)$$

where

$\lambda_0 = L \prod_{\theta_2} \underline{T}_{\theta_2} + (1-L) \sum_k (-1)^{J-k} (\underline{T}_k)^{J-1} \prod_{\theta_2; k \ni \theta_2} \underline{T}_{\theta_2}$, and

$$\lambda_j = L \prod_{\theta_2} \underline{T}_{\theta_2} + (1-L)(-1)^{J-j} (\underline{T}_j)^{J-1} \prod_{\theta_2; j \ni \theta_2} T_{\theta_2} \ , \quad j>0 \ . \quad (38)$$

Let us now rearrange (16) as follows:

$$L \underline{T}_m \sum_j p_j E[l_{c,j}] \prod_{k \neq j} (1-p_k) - L p_m \prod_{k \neq m} (1-p_k) + L \underline{T}_m + \underline{T}_m (1-L) \prod_j (1-p_j) = 0, \quad (39)$$

and by substituting again (36) and (35) in the previous expression it leads to a second linear expression:

$$\sum_j \xi_j p_j = \xi_0 \ , \quad (40)$$

where

$\xi_0 = L \sum_j (-1)^{J-j} E[l_{c,j}] \sum_k \underline{T}_j (\underline{T}_k)^{J-2} \prod_{\theta_2; k \ni \theta_2} \underline{T}_{\theta_2} + L \prod_{\theta_2} \underline{T}_{\theta_2} + (1-L) \sum_k (-1)^{J-k} (\underline{T}_k)^{J-1} \prod_{\theta_2; k \ni \theta_2} \underline{T}_{\theta_2} + L \sum_k (-1)^{J-k} (\underline{T}_k)^{J-2} \prod_{\theta_2; k \ni \theta_2} \underline{T}_{\theta_2}$

and

$\xi_j = L \sum_k (-1)^{J-j} E[l_{c,k}] \underline{T}_k (\underline{T}_j)^{J-2} \prod_{\theta_2; j \ni \theta_2} \underline{T}_{\theta_2} - L (-1)^{J-j} (\underline{T}_j)^{J-2} \prod_{\theta_2; j \ni \theta_2} T_{\theta_2} + (1-L)(-1)^{J-j} (\underline{T}_j)^{J-1} \prod_{\theta_2; j \ni \theta_2} T_{\theta_2}, \quad j>0$

It is now possible to multiply (37) by $1/\lambda_1$ and (40) by $-1/\xi_1$ and add them so as to drop the variable p_1, which yields:

$$\sum_{j=2} p_j (\lambda_j/\lambda_1 - \xi_j/\xi_1) = (\lambda_0/\lambda_1 - \xi_0/\xi_1). \quad (41)$$

By substituting (40) and (41) back in (33) and solving the resulting system of equations for the remaining variables leads to a set of expressions for each p_j independent of other p_k's. If these expressions are substituted back again in (33) then we obtain an explicit non-parametric formula of the throughput region. Since a generalized expression results too complex, we will deal in the following subsection with a simplified system with only two users.

Two-user Systems

Let us now focus on a scenario with two users J=2. It can be easily proved that (37) takes the following form

$$p_1 (L \underline{T}_2 - \underline{T}_1) + p_2 (\underline{T}_2 - L \underline{T}_1) = \underline{T}_{21} \ . \quad (42)$$

Similarly, (40) for two-user systems reduces to:

$$p_1[-(1-L)\underline{T}_1-L+L\delta] + p_2[(1-L)\underline{T}_2+L-L\delta] = \underline{T}_{21}\ . \qquad (43)$$

where $\delta = E[l_{c,1}]\underline{T}_1 + E[l_{c,2}]\underline{T}_2$. The solutions for this system of equations are given by:

$$p_1 = (\eta-\underline{T}_{21})/[(1-L)(\underline{T}_1+\underline{T}_2)+ \eta(L+1)\ ], \qquad (44)$$

and a similar expression for p_2, where η =1-δ. By substituting these solutions for p_1 and p_2 in (33) and after some algebraic manipulations we obtain:

$$(1-L)\ y^2 +2y\eta L - x^2 = \eta^2 L, \qquad (45)$$

which is the expression of a conic section, and where $x=\underline{T}_{21}$ and $y=\underline{T}_1+\underline{T}_2$. This means that the throughput region is bounded by a conic section that is aligned across the axes defined by x and y. Note that by using carrier sensing ($L > 1$) the curve becomes an ellipse, whereas when no carrier sensing is performed ($L = 1$) the expression boils down to a parabola. The use of cooperation is reflected on the value of η, which affects the parameters of the conic curve (rotation angle and shifting).

Markov Model

For purposes of stability analysis, users in the network will be modeled in two states: idle and backlog (see Fig. 2). Let us define the state of the network at epoch-slot q as the set of users U_q that are in the backlog state. The transition probability between two states of the network in consecutive epoch slots can be calculated by considering all possible combinations of users that either enter or exit the backlog state. Four useful cases can be identified: 1) when the number of backlogged users drops by one, which means that a successful transmission of one of the backlogged users took place during the current epoch; 2) when the number of backlogged users increases by one, which means that only one idle user has transmitted and its reception has failed; 3) when the number of backlogged users increases by more than one, which means that more than one idle users have transmitted and collided; and 4) when the number of backlogged users does not change. In the latter case two subcases can be further identified: one where an idle user is correctly decoded with all backlogged users remaining inactive, and another one where idle users remain inactive while none of the backlogged users is correctly detected by the destination. These cases can be written in mathematical form as follows:

$$\Pr\{\ U_{q+1} \mid U_q\ \} =$$
$$p_{r,j}p_{s,j}\prod_{k\varepsilon U_q,k\neq j}(1-p_{r,k})\prod_{m\ni U_q}(1-p_{a,m})\ ,\ \ j\varepsilon\ U_q,\ \ j\ni\ U_{q+1}\ ,\quad K=-1;$$
$$\sum_{j\ni U_q}p_{a,j}p_{s,j}\prod_{k\varepsilon U_q}(1-p_{r,k})\prod_{m\ni U_q,m\neq j}(1-p_{a,m})+[1-\sum_{j\in U_q}p_{r,j}p_{s,j}\prod_{k\varepsilon U_q,k\neq j}(1-p_{r,k})]\ \prod_{m\ni U_q}(1-p_{a,m}),\qquad K=0;$$
$$p_{a,j}(1-p_{s,j})\prod_{k\varepsilon U_q}(1-p_{r,k})\ \prod_{m\ni U_q u U_{q+1}}(1-p_{a,m})\ ,\ \ j\ni U_q,\ j\varepsilon U_{q+1}\ \ K=1;$$
$$\prod_{k\ni U_q,k\varepsilon U_{q+1}} p_{a,k}\prod_{m\ni U_q u U_{q+1}}(1-p_{a,m}),\quad K>1, \qquad (47)$$

where $K=|U_{q+1}|-|U_q|$, and $|.|$ is the set cardinality operator. Let us now arrange the probability of occurrence of all the possible sets of backlogged users $\Pr\{U_q\}$ into a one-dimensional vector given by $\mathbf{s}=[s(0),\ \ldots\ ,\ s(J^I)]^T$, where $(.)^T$ is the vector transpose operator (see Fig. 3). This means that we are mapping the asymmetrical states into a linear state vector where each element represents the probability of occurrence of one different state $\Pr\{U_q\}$. In the example given in Fig. 3, we have only two possible users, where the first system state is given by both users as idle, the second state with only user 1 as idle, the third state with both users in the backlog state, and the fourth state with only user 2 as idle. Once these states are mapped into the state vector $\mathbf{s}$, the transition probabilities between such states $\Pr\{U_{q+1}|U_q\}$ can also be mapped into a matrix $\mathbf{M_e}$, which defines the Markov model for state transition probabilities (see Fig. 3). The (i,j) entry of the matrix $\mathbf{M_e}$ denotes the transition probability between state i and state j. The vector of state probabilities can thus be obtained by solving the following characteristic equation:

$$\mathbf{s}=\mathbf{M_e}\ \mathbf{s}, \qquad (48)$$

using standard eigenvalue analysis or iterative schemes. Each one of the calculated terms of the vector $\mathbf{s}$ can be mapped back to the original probability space $\Pr\{U_q\}$, which can then be used to calculate relevant performance metrics.

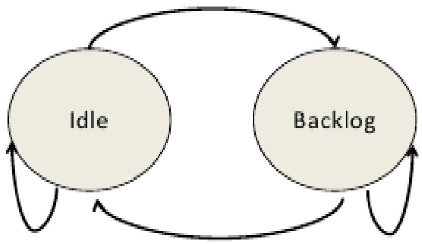

FIG. 2 STATE-MODEL FOR EACH USER IN THE NETWORK

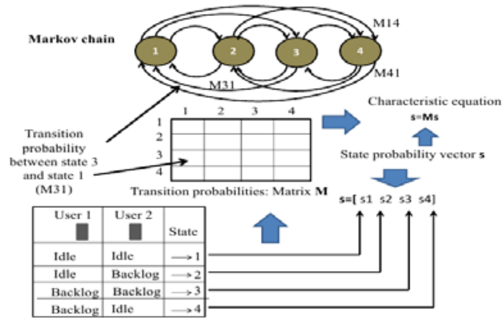

FIG. 3 EXAMPLE OF THE MARKOV MODEL FOR A TWO-USER SYSTEM

The correct packet transmission probability per epoch can be obtained by adding all the contributions over the probability space $\Pr\{U_q\}$. This calculation can be mathematically expressed as:

$$S_j = \sum_{U_q; j \in U_q} \Pr\{U_q\} p_{r,j} \prod_{k \varepsilon U_q, k \neq j} (1-p_{r,k}) \prod_{m \ni U_q} (1-p_{a,m}) p_{s,j}$$
$$+ \sum_{U_q; j \ni U_q} \Pr\{U_q\} p_{a,j} \prod_{k \varepsilon U_q} (1-p_{r,k}) \prod_{m \ni U_q;\, m \neq j} (1-p_{a,m}) p_{s,j} \quad (49)$$

The average length of an epoch in the steady state can then be calculated over the probability space as:

$$E[l] = \sum_{U_q} \Pr\{U_q\} \sum_{j \in U_q} p_{r,j} \sum_{j \in U_q} p_{r,j} \prod_{k \varepsilon U_q, k \neq j} (1-p_{r,k}) \prod_{m \ni U_q} (1-p_{a,m}) E[l_{c,j}] + \sum_{U_q} \Pr\{U_q\} \sum_{j \ni U_q} p_{a,j} \prod_{k \varepsilon U_q} (1-p_{r,k}) \prod_{m \ni U_q; m \neq j} p_{a,m} E[l_{c,j}] + L + (1-L) \sum_{U_q} \Pr\{U_q\} \prod_{j \varepsilon U_q} (1-p_{r,j}) \prod_{k \ni U_q} (1-p_{a,k}) \ . \quad (50)$$

Finally, the throughput of user j can be obtained as the ratio of the correct reception probability per epoch-slot from (49) to the average length of an epoch in the steady state from (50):

$$T_j = LS_j / E[l]. \quad (51)$$

As a measure of stability , we will use probability of a user being in the backlog state

$$p_{b,j} = \sum_{U_q; j \in U_q} \Pr\{U_q\}. \quad (52)$$

The backlog probability of a given user in the network is a measure of the instability of the system: a high probability means the user is most of the time trying to retransmit a packet previously lost rather than attempting the transmission of new incoming packets. The average backlog delay can also be calculated, using an extension of Little's theorem (Tobaggi, 1977), as the ratio of the probability of a user being in the backlog state from (52) to the outgoing traffic from (49):

$$D_{b,j} = p_{b,j} / S_j \ . \quad (53)$$

In this paper we will evaluate fairness by means of the Gini index, which is commonly used in the field of economics. The index can be mathematically written as (Marshall,1979):

$$F_G = \sum_j \sum_{k \neq j} | T_j - T_k | / (2J \sum_j T_j). \quad (54)$$

A value of the Gini index close to zero means the highest degree of fairness, while a value close to one is related to a worsening of fairness conditions (Marshall,1979).

Results

Let us now present some results that show the properties of the proposed algorithm. Fig. 4 and Fig. 5 present the sketches of the throughput region as described by (16) and (19), using two subsets of users with equal number of users (J_1=J_2). Two cases are displayed: Fig. 4 with J_1=J_2=1 and Fig. 5 with J_1=J_2=4. The results have been calculated for the conventional S-ALOHA protocol (L=1) and for a system with carrier-sensing (L=2). In both cases, the non-cooperative (M=1) and cooperative mode (M=2) have been included. Users in the first set have low reception probabilities with parameter $\gamma_{1,1}$ =1, while in the second set, high reception probabilities are experienced with parameter $\gamma_{2,1}$=10. User to user communication is implemented with parameters $\gamma_1^{(2)}$= $\gamma_2^{(1)}$=8, $\gamma_1^{(1)}$ =4, and $\gamma_2^{(2)}$=10. The reception threshold is set to β=1. Note in Fig. 4 and Fig. 5 that cooperation considerably improves the performance of the group of users with low reception probabilities, whereas in the case of carrier sensing, the improvement seems to be equal for both groups regardless of their channel statistics. In all cases we observe an increase in the area of the throughput region. In the particular case of J_1=J_2=1 in Fig. 4 it can be observed that the boundary of the throughput region acquires a shape that resembles a conic section, as demonstrated in (46).

Fig. 6 shows the results for the system throughput calculated by means of the Markov model characteristic equation in (47) for a system with two subsets of users, each one with J_1=J_2=8 users. Results were calculated with the same reception parameters as in the previous example and with a fixed packet transmission probability in the idle state of p_a=0.1. It can be observed that cooperative diversity (M=2) and carrier-sensing (L=2) provide the maximum gain in terms of stable throughput. In terms of stable performance, Fig. 7 shows the average number of users in the backlog state, where the use of cooperative diversity helps in the reduction of the number of backlogged users and thus contributes to the stable operation of the protocol. In contrast to carrier-sensing, cooperative diversity also yields the reduction in the Gini index in (54) as shown in Fig. 8. Also note in Fig. 8 that the effects of carrier-sensing on fairness are imperceptible, as carrier-sensing tends to improve overall channel utilization rather than the reception probability of users that due to bad channel conditions required some kind of cooperation. The particular reception parameters used in this section allowed for a good cooperation scheme where users with good channels successfully relay packets of users with bad channels, which results in a reduction of the Gini index to almost zero.

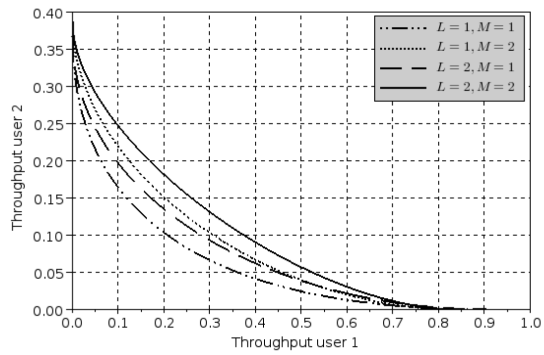

FIG. 4 THROUGHPUT REGION FOR SYSTEMS WITH TWO SUB-SETS OF USERS WITH COOPERATION AND CARRIER SENSING

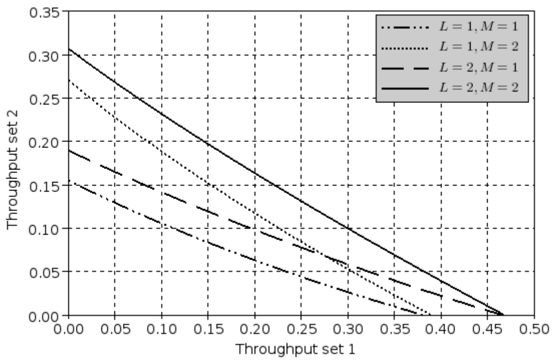

FIG. 5 THROUGHPUT REGION FOR SYSTEMS WITH TWO SUB-SETS OF USERS WITH COOPERATION AND CARRIER SENSING

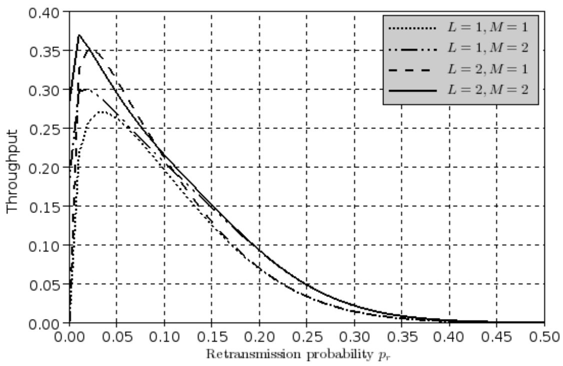

FIG. 6 AVERAGE SYSTEM THROUGHPUT (*T*) VS. BACKLOG RETRANSMISSION PROBABILITY WITH A PACKET TRANSMISSION PROBABILITY IN IDLE STATE OF P_A=0.1

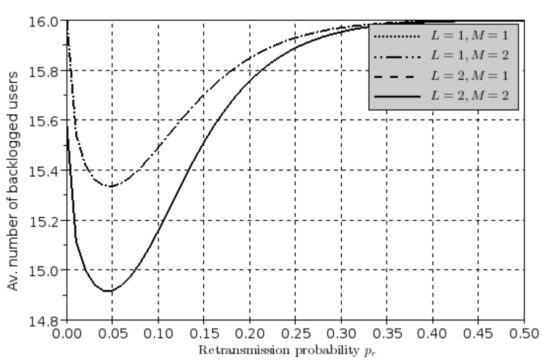

FIG. 7 AVERAGE NUMBER OF BACKLOGGED USERS VS. BACKLOG RETRANSMISSION PROBABILITY WITH A PACKET TRANSMISSION PROBABILITY IN IDLE STATE OF P_A=0.1

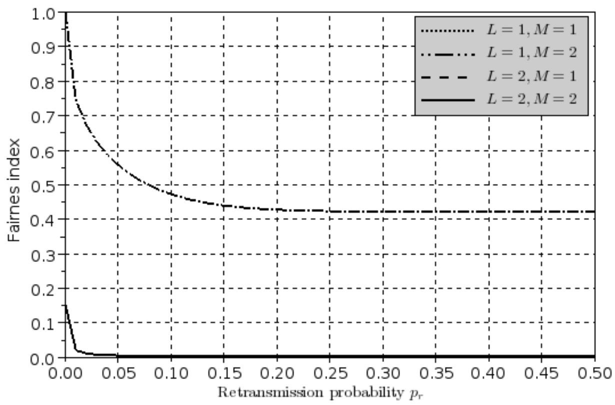

FIG. 8 GINI FAIRNESS INDICATOR (F_G) VS. BACKLOG RETRANSMISSION PROBABILITY WITH A PACKET TRANSMISSION PROBABILITY IN IDLE STATE OF P_A=0.1

Conclusions

This paper has presented the MAC-PHY cross-layer design of a class of carrier-sense multiple access protocol where users with good channel states can cooperate with users with bad channel states by relaying a copy of collision-free signals. A packet reception model with closed-form expressions in Rayleigh channels, which is suitable for MAC/PHY co-design, was used in the investigation. The boundaries of the throughput region were derived in closed-form parametric expression. Sketches of the throughput region indicate that carrier-sensing increases the area of the throughput region indistinctively for users with good or bad channel conditions. By contrast, cooperation improves performance mainly for users with bad channel states. A method for obtaining non-parametric expressions of the boundaries of the throughput region was further proposed. In the case of two-user systems, the boundaries boil down to a conic section whose shape depends on the use of cooperation or carrier-sense. A Markov model was further proposed for analysis of stability and fairness aspects. Carrier sensing was proved useful only for overall system throughput, whereas cooperation was found useful for reducing the average number of backlogged users and for improving fairness (reduction of the Gini index).

Appendix

Partial Fraction Expansion (PFE) of (6)

Let us multiply (6) by $(-\gamma_{j,1})^{-1}(-\upsilon_j)^{1-n}$ so that it takes the standard PFE form:

$$\Psi_{\Gamma_{j,n}}(\mathrm{i}\omega) = (-\gamma_{j,1})^{-1}(-\upsilon_j)^{1-n}\underline{\Psi}_{\Gamma_{j,n}}(\mathrm{i}\omega), \quad (55)$$

where

$$\underline{\Psi}_{\Gamma_{j,n}}(\mathrm{i}\omega) = (\mathrm{i}\omega\text{-}1/\gamma_{j,1})^{-1}(\mathrm{i}\omega\text{-}1/\upsilon_j)^{1-n}, \quad (56)$$

The expression in (56) can be identified as a standard PFE problem with repeated roots (Connexions,2012) that can be expanded as follows:

$$\underline{\Psi}_{\Gamma_{j,n}}(\mathrm{i}\omega) = \underline{A}_j(\mathrm{i}\omega\text{-}1/\gamma_{j,1})^{-1}+\sum^{n-1}_{m=1}\underline{B}_{j,m}(1\text{-i}\omega\,\upsilon_j)^{-m}, \quad (57)$$

where the coefficients $\underline{A}_j$ and $\underline{B}_{j,m}$ can be calculated as (Connexions,2012):

$$\underline{A}_j = (\mathrm{i}\omega\text{-}1/\gamma_{j,1})\underline{\Psi}_{\Gamma_{j,n}}(\mathrm{i}\omega)\,|_{(\mathrm{i}\omega=1/\gamma_{j,1})} = (1/\gamma_{j,1}\text{-}1/\upsilon_j)^{1-n},$$

and

$$\underline{B}_{j,m} = (1/(n\text{-m})!)(d^{m-n}/d(\mathrm{i}\omega)^{m-n})[(1\text{-i}\omega\upsilon_j)^{n-1}\underline{\Psi}_{\Gamma_{j,n}}(\mathrm{i}\omega)\,|_{(\mathrm{i}\omega=1/\upsilon_j)} = (1/\upsilon_j\text{-}1/\gamma_{j,1})^{m-n}$$

The coefficients of the original non-standard PFE problem can be calculated by modifying (57) back to a useful representation for the back-transform:

$$\underline{\Psi}_{\Gamma_{j,n}}(\mathrm{i}\omega) = (\text{-}\gamma_{j,1})^{-1}\underline{A}_j(\mathrm{i}\omega\text{-}1/\gamma_{j,1})^{-1}+\sum^{n-1}_{m=1}(\text{-}\upsilon_j)^{m-n}\underline{B}_{j,m}(1\text{-i}\omega\upsilon_j)^{m} \quad (58)$$

Let us multiply the coefficients in the previous expression by the term $(\text{-}\gamma_{j,1})^{-1}(\text{-}\upsilon_j)^{1-n}$ to revert the operation that led to (56):

$$A_j=(\text{-}\upsilon_j)^{1-n}\underline{A}_j \quad \text{and} \quad B_{j,m}=(\text{-}\gamma_{j,1})^{-1}(\text{-}\upsilon_j)^{1-m}\underline{B}_{j,m},$$

which leads to the expressions in (7).

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