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협력적 스펙트럼 공유의 자동 반복 프로토콜

An Automatic Repeating Protocol in Cooperative Spectrum Sharing

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요 약 본 논문에서는, NACK 메시지가 스펙트럼 공유와 협력을 위한 명령으로 사용되어지는 방법을 제안하였다. 1차 사용자의 직접 연결이 중단될 때, 협력과 공유의 자동 반복을 허가하고, 패러다임 기반의 협력 스펙트럼 공유의 조정 메시지의 수를 절약하기 위해 허가한다. 공유 시, α의 남은 전력 부분이 1차 재전송 신호인 동안, 2차 전송된 신호를 위한 $1-\alpha$ 전력 부분은 중계기 공유로 선택된다. 중계기를 사용하지 않는 경우, 1차 송신단은 전체 전력 $(1-\alpha)$를 사용하여 신호를 재전송하기위해 NACK를 사용한다. 두 시스템은 BPSK 신호를 적용한 것으로 가정한다. 이 기법에서, 2차 사용자는 공동 최적화 복호를 하는 것으로 제안한다. 프레임 오류율(FER) 성능은 양 시스템에서 분석된다. 이론과 시뮬레이션 결과는 본 프로토콜의 유효성을 분석하고 효율적임을 확인하였다.

Abstract In this paper, we propose a method in which the negative acknowledge (NACK) message is used as command for cooperation and spectrum sharing. This allows for an automatic request for cooperation and sharing when the direct link of the primary user is in outage, and also allows for saving the number of control messages in cooperation-spectrum sharing based paradigm. In the sharing phase, the selected relay shares a power fraction of $1-\alpha$ for secondary transmitted signal while the remaining of α is for primary retransmitted signal. In the case of no relay collected, primary transmitter uses NACK as a command to retransmit the signal with fully power fraction $(\alpha=1)$. Both systems are assumed to employ BPSK signals. In this scheme, we propose the joint optimal decoding in the secondary user. The frame error rate (FER) performance at both systems is then analyzed. The theoretical and simulation results validate the analysis and confirm the efficiency of the protocol.

Key Words : Cognitive Radio, estimation, composite detection, spectrum sensing, UMP test.

Ⅰ. Introduction

The under-utilization in spectrum [1-2] and the explosive growth of wireless systems has increased the great deal of interest in cognitive radio technology, which consists of “detect-and-avoid” protocols [3] and dynamic spectrum leasing models [3-6].

There has been a number of spectrum sharing models for cognitive radio have been proposed [7-11] so far. Cooperative spectrum sharing allows the secondary nodes to assist primary transmission to compensate for the degradation which is caused by

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their interception[7-9]. With the knowledge about instantaneous or statistical channel information, the primary users are able to decide how much of the spectrum should be shared to the secondary system [9, 11]. The severity of cooperation between two systems can be controlled by secondary users by exploiting a multi-radio scheme as mentioned [12].

The co-existence of both systems causes a numerous of control messages because the spectrum sharing requires the primary link to be aware of the number and identity of secondary nodes which are available in the spectrum band. In practice, the co-existing system encounters a more complexity because the frequency and time resources for control channels are limited. Therefore, the price paid for spectrum sharing is the complicating control channels, and the relevant reduction in the spectral efficiency.

In this article, we attempt to reduce the number of control message by proposing the use of the NACK message as as the command for cooperation and spectrum sharing. This message is launched by the primary destination D_p when the direct transmission is unsuccessful decoded. Transmissions for a primary packet are divided two phases: the mandatory and the cooperation-sharing phases. In the mandatory phase, the primary transmitter (T_p) transmits a packet to D_p, which is also received by other secondary users. A positive acknowledge (ACK) message is responded by D_p if it successfully decodes the primary packet. Otherwise, a NACK is replied in order to request a retransmission and to allow spectrum sharing. A secondary user which successfully decodes the primary packet in the first phase superposes the secondary signal with a fraction of power of $(1-\alpha)$ on the primary signal which is allocated with a fraction of power $\alpha, 0 \leq \alpha \leq 1$ [11]. When no relay is collected, the transmitter T_p regenerates the primary packet with full fraction of power $(\alpha = 1)$. In the previous study [11], Yang et al simply investigated the outage performance of the cooperation-spectrum sharing based paradigm. However, the FER performance has not been considered.

The remainder of this paper is organized as follows. The next section describes the system model. In Primary Frame Error Rate Analysis section, performance of FER in the primary is analyzed. The Numerical and Simulation Results section evaluates the aforementioned analysis. The Conclusion section will conclude our work.

II. System Model

The system consists of pair of the primary transmitter and receiver T_p and D_p, a set of M_{tot} secondary transmitters which is defined as $S_{tot} = R_{S_i}, i = 1,2,...,M_{tot}$, and a common secondary receiver D_S . We further denote A, where A subset S_{tot}, as the active set which are composed of M users, $M \leq M_{tot}$, ready for the cooperation and sharing. For the simplification, we assume that all of users in A have demand of secondary transmission. Before the start of the mandatory transmission, T_p and D_p exchange a several messages. They are the primary request-to-send (RTS) message which is denoted as RTS_p, and primary clear-to-send (CTS) which is denoted as CTS_p. The primary transmission uses only the mandatory phase if the node D_p transmits the primary positive acknowledgement (ACK_p) to indicate its successful decoding. Otherwise, the primary system requires another phase, known as the cooperation and sharing phase; the node D_p transmits a primary negative acknowledgement $(NACK_P)$ to request for this phase. We denoted $R_{\tilde{A}_i}$ as the user which is selected to be primary relay among the users in group A. The node $R_{\tilde{A}_i}$ must be the node which successfully decodes the primary signal in the first phase. This nodes then composes a composite signal consisting of primary signal with respect to power allocation factor α, and secondary signal with respect to $1-\alpha$ [11] in order to implement the both of cooperation and spectrum sharing. If no user in group A correctly decodes primary signal, the primary transmitter T_p will retransmit its signal. The base-band received signal at node j sent from node i for a l-th symbol is generally given by

$$y_{ij}(l)= \sqrt{E_P}h_{ij}s(l)+n_j(l) \tag{1}$$

h_{ij} is denoted as channel coefficients between two nodes of i and j . n_j is denoted as the noise at the node j , and modeled as the complex AWGN noise with zeros mean and variance $2\sigma^2$. The $s(l)$ is the transmit signal of the node i at the l-th symbol. When the node i is the primary transmitter, s is replaced by s_p which is denoted as the primary signal. When the node i is the secondary transmitter, the signal s is replaced with $s_s(l)$ which is the secondary signal. We assume that fading is the slow Rayleigh fading where the average power gain of the link between node i and j is denoted as $\Omega_{ij}, \Omega_{ij}= \frac{1}{d^{\nu_{ij}}}$, where d_{ij} is distance between node i and j while v is the path loss. In the scope of this article, we assume that $d_{ij}=d \ \forall\,(i,j) \neq \left\{\left(T_{p,D_p}\right),\left(T_{p,R_{S_i}}\right),(R_{S_i},D_{p)}\right\}$. When the nodes R_{S_i} locate nearby each other and the distances from D_s to R_{S_i} are sufficiently large, the distance from R_{S_i} to D_s is approximated $d_{R_{S_i}D_s}=d$.

When T_p and D_p locate nearby to each other and sufficiently large to the relay group, we can approximate that $d_{T_{pR_{S_i}}}=d_{R_{S_i}D_p}=d_{SP}$. The average power gain of channel between T_p and D_p is $\Omega_{T_pD_p}=\frac{1}{d^v_{T_pD_p}}$. The average power gain of primary transceivers and relays are denoted as $\Omega_{PS}=\Omega_{T_{pR_{S_i}}}=\Omega_{R_{S_i}D_p}=\frac{1}{d^{v_{SP}}}$. While for the link $R_{S_i}-D_s$, it is $\Omega=\Omega_{R_{S_i}D_s}=\frac{1}{d^v}$. Powers of the primary and secondary signal are set equally as $E_P=E_S=E$ respectively. $s_p(l)$ and $s_s(l)$ are the BPSK modulated signals that carry a bit message encoded by a convolutional encoder with generators G_1 and G_2, respectively. For tractability in presentation, we define by $\gamma_{ij}=\frac{|h_{ij}|^2\times E}{2\sigma^2}$ and denote $\tilde{\gamma}_{ij}$ as the SNR at node i with respect to signal transmitted from node j. For primary links, probability power function (PDF) is given as,

$$\begin{aligned}
&f_{\gamma_{T_{pD_p}}}(x)=\frac{1}{\Gamma_P}\exp\left(-\frac{x}{\Gamma_P}\right),\Gamma_{P=E_P}\times\frac{\Omega_{T_{pD_p}}}{2\sigma^2};\\
&f_{\gamma_{ij}}(x)=\frac{1}{\Gamma}\exp\left(-\frac{x}{\Gamma}\right),\Gamma=E\times\frac{\Omega}{2\sigma^2}, \ ;\\
&(i,j)\neq\left\{\left(T_p,D_p\right),\left(T_p,R_{S_i}\right),(R_{S_i},D_{p)}\right\}\\
&f_{\gamma_{ij}}(x)=\frac{1}{\Gamma_{\mathrm{PS}}}exp\left(-\frac{x}{\Gamma_{\mathrm{Ps}}}\right),\Gamma_{\mathrm{PS}}=E\times\frac{\Omega_{\mathrm{PS}}}{2\sigma^2},\\
&(i,j)\in\left\{\left(R_{S_k},T_p\right),\left(D_p,R_{S_k}\right)\right\}
\end{aligned} \tag{2}$$

III. Performance Analysis

In the first phase transmission, the upper-bound of average FER at D_p using approach of [14] is calculated as follows:

$$P^{(1)_{FER,\,T_{pD_p}}}\leq\int_0^\infty \min\left\{\begin{array}{l}1,B_1\sum\limits_{d_1=d_{free}}^{\infty}a_{G_1}^{(1)}(d_1)\\ \times P_{PEP,D_p}^{(1)}\left(d_{1,x|}\widetilde{\gamma_{T_{pD_p}}}\right)\end{array}\right\}f_{\widetilde{\gamma_{T_pD_p}}}(x)dx \tag{3}$$

where $B_1=B$ is denoted as the number of bits per frame, d_{free} is the free distance of code and $a_P^{(1)}$ is the number of error events with respect to Hamming distance d_1 and the correspondent code generator G_1.

Pair-wise error probability with respect to a given SNR and Hamming distance is denoted as $P^{(1)}_{PEP,D_p}$ where $P^{(1)}_{PEP,T_{pD_p}}\left(d_1|\tilde{\gamma}_{T_{pD_p}}\right)=Q\left(\sqrt{2d_1\tilde{\gamma}_{T_pD_p}}\right)$. It should be noted that the upper subscript indicating transmission phase, $Q(.)$ is the Gaussian Q function, $\tilde{\gamma}_{T_pD_p}=\gamma_{T_pD_p}$. The average FER performance of the user in the active set users can be derived in the similar way with the use of PDF of $f_{\tilde{\gamma}_{T_pR_{A_i}}}(x)$. Denote average FER at a relay R_{A_i} as $P^{(1)}_{FER,R_{A_i}}$, the probability of successfully select a $R_{\tilde{A}_i}$ is given as follows,

$$P^{(1)}_{sel,R_{\tilde{A}_i}}=1-\prod_{i=1}^{M}P^{(1)_{FER,R_{A_i}}}=1-\left(P^{(1)}_{FER,R_{A_i}}\right)^M \tag{4}$$

After receiving NACK_P and complete procedure for secondary transmission request, $R_{\tilde{A}_i}$ generates the a composite signal consisting of primary and secondary signal. The primary retransmitted signal is encoded using the code generator G_2 while the secondary is encoded using G_2. The composite signal received by D_p is expressible as,

$$y_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}\mathrm{D}_\mathrm{p}}(l)=\begin{bmatrix}\sqrt{\alpha E_p}\times s_p(l)\\+\sqrt{(1-\alpha)E_s}\times s_s(l)\end{bmatrix}h_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}\mathrm{D}_\mathrm{p}}+n_{D_p}(l) \tag{5}$$

with the respected SNR is given as,

$$\begin{aligned}\tilde{\gamma}_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}&=\frac{\alpha E_p\left|h_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}\right|^2}{(1-\alpha)E_s\left|h_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}\right|^{2+}\sigma^2}\\&=\frac{\alpha\gamma_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}}{(1-\alpha)\gamma_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}+1}\le\frac{\alpha}{1-\alpha}\end{aligned} \tag{6}$$

At D_p, the equally gain combining signal of $y^{(1)}_{T_pD_p}$ (primary signal at D_p in mandatory phase) and $y_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}$ are decoded. Therefore, it is similar to (3), FER performance of D_p in this case is rewritten as follows,

$$\begin{aligned}&P^{(2)(NACK_{P})_{FER,\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}}\le\\&\int_0^\infty\int_0^\infty\min\begin{cases}1,\\B_2\sum_{\underline{d}=d_{1f},d_{2f}}^{\infty}a(d_{1,d_2})\\\times P^{(2)(NACK_{P})_{PEP,\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}},D_p}}\left(d_1,x,d_2,y|\tilde{\gamma}_{T_pD_p}\right)\\\times f_{\gamma_{T_pD_p}}(x)f_{\gamma_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}}(y)dxdy\end{cases}\end{aligned} \tag{7}$$

where $B_2=2B$ if G_1 and G_2 uses the same code rate. According to Appendix, $P^{(2)(NACK_{P})}_{PEP,D_p}$ is given as,

$$\begin{aligned}&P^{(2)(NACK_P)}_{PEP,R_{\tilde{A}_iD_p}}=\left(\frac{1}{2}\right)^{d_2}\Sigma^{d_2}_{k=0}\binom{d_2}{k}\\&\times Q\left(\frac{2(2k-d_2)\sqrt{\alpha(1-\alpha)}\times\gamma_{T_{pD_p}}+2\left(d_1\gamma_{T_{pD_p}}+\alpha d_2\gamma_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}\right)}{\sqrt{2\left(d_1\gamma_{T_{pD_p}}+\alpha d_2\gamma_{\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}\right)\}}}\right)\end{aligned} \tag{8}$$

Performance respect to that no user in active set is able to correctly decode primary users is dependent on the combination signal of $y^{(1)}_{T_pD_p}$ and $y^{(2)}_{T_pD_p}$. Denoting the FER in this case as $P^{(2)(NACK_P)}_{FER,T_{pD_p}}$, it is similar to (7) in order to obtain the FER performance of this case using the PEP $P^{(2)(NACK_P)}_{PEP,T_{pD_p}}=Q\left(\sqrt{2d_1\tilde{\gamma}^{(1)}_{T_pD_p}+2d_2\tilde{\gamma}^{(2)}_{T_pD_p}}\right)$.

As the number of primary packets approaches to infinitive, it is obvious that the overall FER performance of primary system in cooperation-sharing phase, denoted as $\overline{P}^{(2)(NACK_P)}_{FER,D_p}$ is belonged to $P^{(1)}_{sel,R_{\tilde{A}_i}},P^{(2)(NACK_{P})}_{PEP,T_pD_p}$, $P^{(2)(NACK_{P})}_{PEP,\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}$ as follows,

$$\begin{aligned}&\overline{P}^{(2)(NACK_{P})}_{FER,D_p}=\\&P^{(2)(NACK_{P})}_{PEP,T_{pD_p}}\times\left(1-P^{(1)}_{sel,R_{\tilde{A}_i}}\right)+P^{(2)(NACK_{P})}_{PEP,\mathrm{R}_{\tilde{\mathrm{A}}_\mathrm{i}}D_p}P^{(1)}_{sel,R_{\tilde{A}_i}}\end{aligned} \tag{9}$$

IV. Simulation Results and Discussion

In this section, we provide simulation of FER performance of both systems and average transmission rate of primary system. In the simulation, we assume noise variance σ^2 per dimension equal to 0.5, $d_{T_pD_p}=\sqrt{2}$, $d_{T_{pR_{S_i}}}=d_{R_{S_{iD_p}}}=1$, $d_{R_{S_i}R_{S_j}}=d_{R_{S_i}D_S}=\frac{1}{2}$. Environment path loss exponent is set at $v=2$. The number of secondary users is $M_{tot}=5$. We use convolutional code with constraint length $K=4$ (for all channels) and the polynomial generator $G_1=[17,15]$ for primary link transmission and relay-primary destination transmission. At D_p, because the selected relay employs G_1 for primary signal retransmission, D_p combines signals received in two phases by puncturing the received bit streams of two phases to match with polynomial generator $G=[G_1,G_1]$. Secondary transmission employs a more strong convolutional code with $G_2=[17,15,13,15]$. The number of bits per stream before encoding in any primary transmission is set at $B_P=64$ while size of secondary frame before encoding is $B_S=32$. This entails that the number of bit after encoding in each a single phase transmission is 128 bits per slot.

Fig.1 is shown to investigate FER performance of decoding at primary destination and at secondary users in the mandatory phase. It shows that the theoretical upper-bound graph is approximately parallel to the simulation. For the same FER, the theoretical graph requires 1 dB in energy-noise ratio E_b/N_0 greater than simulation graph. Therefore, the simulation FER performance of primary transmission in this phase can be approximately found by shifting the theoretic graph to the left side one dB.

In order to validate aforementioned analysis of FER in cooperation and sharing phase, we provide the Fig.2 which consists of FER performance of primary transmission corresponding to two cases: source and relay retransmission. In this figure, we also provide FER performance of secondary transmission. The investigation is taken under condition of that power allocation factor at $\alpha=0.8$.

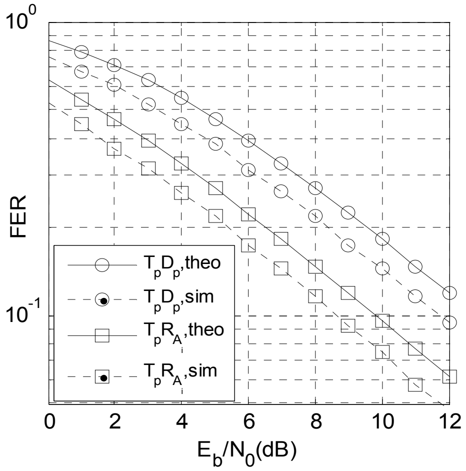

그림 1. 1차 수신단과 2차 사용자의 FER 성능
Fig 1. FER performance at primary destination and secondary user in the mandatory phase.

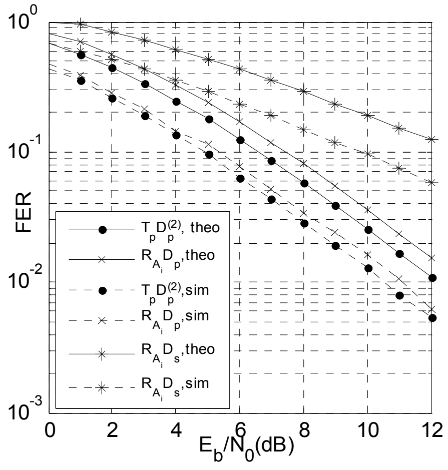

그림 2. $\alpha=0.8$일 때, 협력 공유를 사용한 2차 수신단에서 1차 신호 T_p , $R_{(A_i)}$이 재전송되는 경우 기대되는 1차 수신단의 FER 성능
Fig. 2. FER performance at primary destination respect to cases when T_p and $R_{(A_i)}$ retransmit primary signal, at secondary destination in the cooperation – sharing phase, $\alpha=0.8$.

As observing, the analysis provides the upper-bound of actual performance. As E_b/N_0 increases, the analysis graphs are parallel to the respective simulation graphs. It is required additional 2dB of E_b/N_0 for theory analysis to obtain the same FER with the simulation graph in primary decoding performance while the respective gap in the case of secondary decoding performance is 3dB.

V. Conclusion

In this paper, we propose a scheme to save the number of control messages in cooperation-sharing based spectrum model using the NACK feedback message. It shows that we can save the two control messages of RTS_p and CTS_p for cooperation in primary system. The cooperation and sharing is automatically implemented whenever primary system fails to transmit the primary signal in mandatory phase. Furthermore, we investigate the FER performance in primary and secondary receivers. In this analysis, we study the worst case that secondary receiver cannot decode the primary signal in mandatory.

Appendix

FER performance at D_p when decoding the composite signal is given in this appendix. Denoting y_Σ as this combined signal, y_Σ is explicitly rewritten as given,

$$y_\Sigma(l) = \begin{cases} \sqrt{E_P}\, h_{T_{pD_p}} s_P(l) + n_{D_p}(l) & ,1 \le l \le B \\ \left[\begin{array}{l} \sqrt{\alpha E_p} \times s_P(l) \\ + \sqrt{(1-\alpha)E_s} \times s_s(l) \end{array}\right] h_{\widetilde{R}_{A_i} D_p} + n_{D_p}(l) & ,B+1 \le l \le 2B \end{cases} \tag{10}$$

We denote t_l as the amplitude of primary interference to y_Σ at the l-th sample, $t(l) = \{0 when 1 \le l \le B, \sqrt{(1-\alpha)E_s} when others\}$ and $h(l) = \{h_{T_{pD_p}} when 1 \le l \le B, h_{\tilde{R}_{A_i} D_p} when B+1 \le l \le 2B\}$. At the receiver, maximum likelihood decoder decodes the received signal. We denote x_m as the l-th symbol which is transmitted, $x_m(l) = \sqrt{E_P}\, s_{P,m}(l)$ for $1 \le l \le B$ and $x_m(l) = \sqrt{\alpha E_p}\, s_{P,m}(l)$ for others.

We denote $x_{m'}(l)$ as the symbol which is incorrectly decode. The statistic test to decide between $\underline{s}_{P,m} \text{and} \underline{s}_{P,m'}$ is given as follows,

$$\Theta = \frac{p\left(\underline{y} | \underline{x_m}\right)}{p\left(\underline{y} | \underline{x_{m'}}\right)} = \prod_{l=1}^{2L} \frac{\exp\left(-|y_\Sigma(l) - h(l) x_m(l)|^2 2\sigma^2\right)}{\exp\left(-|y_\Sigma(l) - h(l) x_{P,m'}(l)|^2 2\sigma^2\right)} \tag{11}$$

The error space is identified by $E_{mm'} = \left\{\underline{y}: T = \sum^{2L_{l=1}} h(l)\left(x_{P,m'}(l) - x_{P,m}(l)\right) y_\Sigma(l) < 0\right\}$. Due the fact that $\underline{s}_{P,m} = \{-1,1\}$ and the probability of occurrence for each value is 0.5 , $y_\Sigma(l)$ has the PDF as given:

$$p_{y_{\Sigma(l)}}(y) = 0.5\left[\begin{array}{l} \dfrac{1}{\sqrt{2\pi}\,\sigma} exp\left(-\left(y - h(l) x_{P,m}(l) - h(l)t(l)\right)^2 2\sigma^2\right) \\ + \dfrac{1}{\sqrt{2\pi}\,\sigma} exp\left(-\dfrac{\left(y - h(l) x_{P,m}(l) + h(l)t(l)\right)^2}{2\sigma^2}\right) \end{array}\right] \tag{12}$$

Denote T_l as $T_l = h(l)\left(x_{P,m'}(l) - x_{P,m}(l)\right) y_\Sigma(l)$, the moment generation function (MGF) of T_l is derived as follows,

$$MGF\{T_l\} = \left(\frac{1}{2}\right)^{2L} \prod_{l=1}^{2L} \left[\begin{array}{l} \exp\left(\omega\mu_{1,l} + \dfrac{\omega^2 \sigma_l^2}{2}\right) \\ + \exp\left(\omega\mu_{2,l} + \dfrac{\omega^2 \sigma_l^2}{2}\right) \end{array}\right] \tag{13}$$

where $\mu_{1,l} = h^2(l)\left(x_{P,m}(l) + t(l)\right)\left(x_{P,m'}(l) - x_{P,m}(l)\right)$,

$\mu_{2,l} = h^2(l)\left(x_{P,m}(l)-t(l)\right)\left(x_{P,m'}(l)-x_{P,m}(l)\right)$ and $\sigma^{2^2}_{l=h}(l)\left(x_{P,m'}(l)-x_{P,m}(l)\right)^2\sigma^2$. The equation Eqn (13) is rewritten as follows,

$$\begin{aligned} MGF\{T\} &= \left(\frac{1}{2}\right)^{2L}\exp\left(\frac{\omega^2 \sum\limits_{\substack{l=1 \\ x_{m,l}\neq x_{m',l}}}^{2L}\sigma_l^2}{2}\right) \\ &\times\prod_{l=1}^{2L}\exp\left(\omega h^2(l)x_{P,m}\left(x_{P,m}-x_{P,m'}(l)\right)\right) \\ &\times\prod_{l=1}^{2L}\exp\left(-\omega h^2(l)t(l)\left(x_{P,m}-x_{P,m'}(l)\right)\right) \\ &\times\prod_{l=1}^{2L}\left(1+\exp\left(\omega 2h^2(l)t(l)\left(x_{P,m}-x_{P,m'}(l)\right)\right)\right) \\ &= \left(\frac{1}{2}\right)^{2L}\exp\left(\omega^2\sum_{l=1}^{2L}\sigma_l^2 2\right)g_1\cdot g_2\cdot g_3. \end{aligned} \qquad (14)$$

where

$$g_1 = \prod_{\substack{l=1 \\ x_{m,l}\neq x_{m',l}}}^{2L}\exp\left(\frac{\omega h^2(l)\left|x_{P,m}(l)-x_{P,m'}(l)\right|^2}{2}\right),$$

$$g_2 = \prod_{\substack{l=1 \\ x_{m,l}\neq x_{m',l}}}^{2L}\exp\left(-\omega h^2(l)t(l)\left(x_{P,m}(l)-x_{P,m'}(l)\right)\right),$$

and $g_3 = \prod_{l=1}^{2L}\left(1+\exp\left(\omega 2h^2(l)t(l)\left(x_{P,m}-x_{P,m'}(l)\right)\right)\right)$

Eqn. (ref{appA}) can be rewritten as follows,

$$\begin{aligned} &MGF\{T_l,\omega\} \\ &= \left(\frac{1}{2}\right)^{d_2}\exp\left(\omega^2\frac{\sigma_T^2}{2}\right) \\ &\exp\left(\omega\begin{bmatrix}\left(4d_1\gamma_{T_pD_p}+4\alpha d_2\gamma_{\widetilde{R_{A_i}D_p}}\right)\sigma^2 \\ -4d_2\gamma_{\widetilde{R_{A_i}D_p}}\sigma^2\sqrt{\alpha(1-\alpha)}\end{bmatrix}\right) \\ &\times\left(1+\exp\left(\omega 8\sigma^2\gamma_{\widetilde{R_{A_i}D_p}}\sqrt{\alpha(1-\alpha)}\right)\right)^{d_2} \\ &= \left(\frac{1}{2}\right)^{d_2}\exp\left(\omega^2\frac{\sigma_T^2}{2}\right)\sum_{k=0}^{d_2}(d_2k) \\ &\exp\left(\left(\omega\begin{bmatrix}\left(4d_1\gamma_{T_pD_p}+4\alpha d_2\gamma_{\widetilde{R_{A_i}D_p}}\right)\sigma^2 \\ +4(2k-d_2)\gamma_{\widetilde{R_{A_i}D_p}}\sigma^2\sqrt{\alpha(1-\alpha)}\end{bmatrix}\right)\right) \end{aligned}$$

Using the inverse MGF function we can obtain the pdf of the T as follows,

$$f_T(x) = \left(\frac{1}{2}\right)^{d_2}\sum_{k=0}^{d_2}\binom{d_2}{k}\frac{1}{\sqrt{2\pi}}\sigma_T\exp\left(-\frac{\left(x-\mu_{T,k}\right)^2}{2\sigma_T^2}\right)$$

where $\mu_{T,k} = \begin{bmatrix}\left(4d_1\gamma_{T_{pD_p}}+4\alpha d_2\gamma_{\widetilde{R_{A_i}D_p}}\right)\sigma^2 \\ +4(2k-d_2)\gamma_{\widetilde{R_{A_i}D_p}}\sigma^2\sqrt{\alpha(1-\alpha)}\end{bmatrix}$.

The cumulative probability function CDF of Tat $x=0$ using Eqn. (ref{appA}) results in the Eqn. (8).

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