Interference Model and Analysis on Device-to-Device Cellular Coexist Networks

Hao Lu[1,2], Yichen Wang[1,3], Yan Chen[1], and K. J. Ray Liu[1]

[1]Department of Electrical and Computer Engineering, University of Maryland, College Park, MD, 20742 USA
[2]Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei, Anhui, 230027 China
[3]Department of Information and Communications Engineering, School of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049 China
Email: {umdhlu, ycwang, yan, kjrliu}@umd.edu

***Abstract*—Device-to-device (D2D) communications can enhance the overall system capacity by reusing cellular spectrum, which at the same time leads to severe interference to cellular connections and vice versa. In practice, even when two wireless connections share the same spectrum, the interference between them may not always exist if there is no conflict at packet-level transmissions. Thus, in this paper, we establish a cross-layer model for D2D communications underlaying cellular network to characterize the realistic interference scenario. The closed-form stable throughput region between one D2D pair and one cellular link is deduced. Subsequently, our model is extended to a generalized scenario where multiple D2D pairs share the same resources with one cellular link, in which the upper bound of the stable throughput region is derived. As a consequence, the stable throughput regions are significantly enlarged via the proposed model.**

I. Introduction

Device-to-device (D2D) communications serves as a promising technique to improve the overall system capacity since it allows direct transmission between users underlaying cellular networks [1]. In order to improve spectral efficiency, most recent research focused mostly on non-orthogonal sharing mode, where D2D transmitters reuse cellular resources for transmissions [2,3]. Since D2D users (DUEs) may simultaneously reuse an uplink or a downlink resource which is assigned to a cellular user (CUE) by the BS, D2D communications will result in severe interference to the CUE-BS link and vice versa. Efficient resources assignment strategies and power allocation schemes have been proposed to prevent such harmful intra-cell interference [4-6].

There exists a major shortcoming in the related works. The existing works [2-6] were based on information-theoretic studies where both D2D pairs and the cellular connection, which share the same resources, keep transmitting signals simultaneously and interfere with each other all the time. However, in practice, packets are generated and queued for transmission according to certain dynamic processes. Considering the possibility of the transmission queues being empty, all those connections may not access the channel simultaneously within each time slot even when they share the same resources. The underutilization of licensed spectrum has also stimulated the research on cognitive radio [7,8]. Thus, the conventional model fails to capture the real interference scenario.

This work was supported by the National High-Tech Research and Development Plan of China (863 Program) under Grant No. 2014AA01A706, the National Natural Science Foundation of China under Grant No. 61401348, and the Postdoctoral Science Foundation of China under Grant No. 2014M550493.

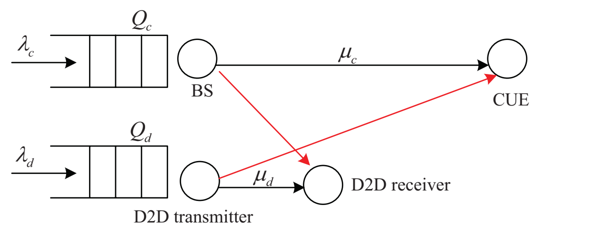


Fig. 1. Queuing and transmission model for single D2D pair scenario. Downlink resources are reused. Red lines represent the interference.

In this paper, we propose a new cross-layer model to characterize the interference between D2D and cellular transmissions. The "cross-layer" notion represents that the proposed model is not only based on physical layer in terms of outage probabilities, but also refers to packet-level queueing and transmission process. Closed-form expression on stable throughput region, when one D2D pair shares the same resources with one cellular link, is derived, where stable throughput region is defined as the set of all arrival rate vectors (in packets/slot) to the sources such that all queues in the network remain bounded [9,10]. Subsequently, the model and analysis will be extended to the generalized case where multiple D2D pairs share the same cellular resources. The upper bound of the stable throughput region are derived to characterize the throughput behavior. As a consequence, the proposed model achieves larger throughput region than that of the conventional model or TDMA orthogonal transmissions. The improvements of the proposed model will be verified through simulations.

Notations: λ, packet arrival rate; μ, packet service rate; ρ, outage probability; $\mathcal{CN}(0,\sigma^2)$, circular symmetric complex Gaussian distribution with zero-mean and variance σ^2; $\exp(1/\sigma^2)$, exponential distribution with mean σ^2; $\Pr\{\text{A}\}$, the probability of event A; $\mathbb{E}$, mathematical expectation.

II. System Model

We consider a hybrid single-cell network, where D2D connections coexist with cellular transmissions. In the single D2D scenario, one D2D pair reuses the same resources with one cellular connection, as depicted in Fig. 1.

The instantaneous channel gain from the transmitter of link i to the receiver of link j ($i, j \in \{c, d\}$) accounts for the path loss and Rayleigh fading, represented by $G_{ij} = L_{ij}^{-\alpha}|h_{ij}|^2$, where L_{ij} is the distance between the node i and j with path-loss exponent α, $h_{ij} \sim \mathcal{CN}(0,1)$ is modeled as zero-mean complex Gaussian random variables with unit variance, characterizing the Rayleigh fading. Thus, $G_{cc} \sim \exp(1/\sigma_c^2)$, $G_{dd} \sim \exp(1/\sigma_d^2)$, $G_{cd} \sim \exp(1/\sigma_{cd}^2)$, and $G_{dc} \sim \exp(1/\sigma_{dc}^2)$ represent the channel gains of the cellular link, the D2D link, channel from the cellular transmitter to the D2D receiver, and channel from the D2D transmitter to the cellular receiver, respectively. All channel coefficients remain constant within one frame and vary independently from frame to frame. The corresponding noise at each receiver is assumed to be complex additive white Gaussian noise (AWGN) with variance N_0. We consider slot-by-slot transmissions. Without loss of generality, let the duration of one time slot (TS) be one packet transmission period.

III. Single D2D Scenario

In the single D2D scenario, as depicted in Fig. 1, packets are generated at the cellular transmitter and D2D transmitter with average rate λ_c and λ_d (packets/slot), respectively, independent from each other and i.i.d over slots. Q_c and Q_d are the transmission queues at the transmitters of the cellular connection and the D2D pair, respectively, with infinite capacity for storing arriving packets. The Loynes' Theorem [11] states that if the arrival and service processes of a queue are strictly stationary and ergodic, the queue is stable if and only if the average arrival rate is strictly less than the average service rate. Thus, the stable throughput region, where one D2D pair and one cellular link share the same resources, is expressed as

$$\mathcal{R} = \{(\lambda_c, \lambda_d)| \quad \lambda_c < \mu_c \quad \& \quad \lambda_d < \mu_d\}, \tag{1}$$

where μ_c and μ_d are the service rates of the cellular link and D2D connection (packets/TS), respectively. We assume that acknowledgements (ACKs) are instantaneous and error-free. The packet that fails to be decoded by the desired receiver will stay in the queue for retransmission. The service rate of each connection is equal to the probability that one packet is successfully decoded at the receiver. Thus we have

$$\begin{aligned}\mu_c &= \Pr\{Q_d = 0\}(1-\rho_c) + \Pr\{Q_d > 0\}(1-\rho_c^{(I)}) \\ &\overset{(a)}{=} \left(1 - \frac{\lambda_d}{\mu_d}\right)(1-\rho_c) + \frac{\lambda_d}{\mu_d}(1-\rho_c^{(I)})\end{aligned} \tag{2}$$

and

$$\begin{aligned}\mu_d &= \Pr\{Q_c = 0\}(1-\rho_d) + \Pr\{Q_c > 0\}(1-\rho_d^{(I)}) \\ &\overset{(a)}{=} \left(1 - \frac{\lambda_c}{\mu_c}\right)(1-\rho_d) + \frac{\lambda_c}{\mu_c}(1-\rho_d^{(I)}),\end{aligned} \tag{3}$$

where $Q_i = 0$ ($i \in \{c, d\}$) denotes that the transmission queue i is empty and no packet is sent within this TS and $Q_i > 0$ corresponds to the case that link i is occupying the channel to perform the transmission, ρ_c is the outage probability of the cellular link when it is free from the interference from D2D link and $\rho_c^{(I)}$ is the outage probability of the interference scenario. Likewise, ρ_d and $\rho_d^{(I)}$ correspond to the outage probabilities of the D2D connection under these two circumstances, respectively. The deducing (a) in (2) or (3) is based on the Little's Law [12], which states that the probability of queue size being equal to zero in a G/G/1 queue with arrival rate λ and service rate μ is $(1 - \frac{\lambda}{\mu})$.

Based on the distributions of the channel gains, the outage probabilities are calculated through

$$\rho_c = \Pr\left\{B\log\left(1 + \frac{P_c G_{cc}}{N_0}\right) < R_c\right\} = 1 - e^{-\frac{N_0\eta_c}{P_c\sigma_c^2}}, \tag{4}$$

$$\rho_d = \Pr\left\{B\log\left(1 + \frac{P_d G_{dd}}{N_0}\right) < R_d\right\} = 1 - e^{-\frac{N_0\eta_d}{P_d\sigma_d^2}}, \tag{5}$$

$$\rho_c^{(I)} = \Pr\left\{B\log\left(1 + \frac{P_c G_{cc}}{P_d G_{dc} + N_0}\right) < R_c\right\} = 1 - \frac{P_c\sigma_c^2\, e^{-\frac{N_0\eta_c}{P_c\sigma_c^2}}}{P_c\sigma_c^2 + \eta_c P_d\sigma_{dc}^2}, \tag{6}$$

and

$$\rho_d^{(I)} = \Pr\left\{B\log\left(1 + \frac{P_d G_{dd}}{P_c G_{cd} + N_0}\right) < R_d\right\} = 1 - \frac{P_d\sigma_d^2\, e^{-\frac{N_0\eta_d}{P_d\sigma_d^2}}}{P_d\sigma_d^2 + \eta_d P_c\sigma_{cd}^2}, \tag{7}$$

respectively, where B is the bandwidth, P_c and P_d are the transmit powers of the cellular transmitter and D2D transmitter, respectively, $\eta_c = 2^{\frac{R_c}{B}} - 1$ and $\eta_d = 2^{\frac{R_d}{B}} - 1$, $R_c = L_c T$ with R_c being the threshold rate related to outage event of cellular link and L_c being the number of bits contained in one packet sent by cellular transmitter. Likewise, R_d corresponds to the D2D link.

Based on (2) and (3), we can obtain the expressions of μ_c and μ_d. Then, according to stable constraint (1), the stable throughput region is given in the following **Theorem 1**.

Theorem 1. *The stable throughput region $\mathcal{R} = \{(\lambda_c, \lambda_d)|\lambda_c < \mu_c \,\&\, \lambda_d < \mu_d\}$, where one D2D pair with packet arrival rate λ_d shares the same resources with one cellular link with λ_c, is characterized by*

$$\mathcal{R} = \left\{(\lambda_c, \lambda_d)\,\middle|\,(\lambda_c, \lambda_d) \in \mathcal{R}_1 \bigcup \mathcal{R}_2\right\} \tag{8}$$

where

$$\mathcal{R}_1 = \left\{\lambda_c < \min\left\{(1-\rho_c) - \lambda_d\frac{\rho_c^{(I)} - \rho_c}{1-\rho_d^{(I)}}, \frac{(1-\rho_d-\lambda_d)(1-\rho_c^{(I)})}{\rho_d^{(I)} - \rho_d}\right\}\right\}, \tag{9}$$

and

$$\mathcal{R}_2=\left\{\lambda_c<\min\left\{\frac{(1-\rho_c)(1-\rho_d)-\lambda_d(\rho_c^{(I)}-\rho_c)}{2-\rho_d-\rho_d^{(I)}},\frac{(1-\rho_d)(1-\rho_c)}{\rho_d^{(I)}-\rho_d}\right.\right.$$
$$\left.\left.-\frac{\lambda_d(2-\rho_c-\rho_c^{(I)})}{\rho_d^{(I)}-\rho_d},\frac{\left(\sqrt{\lambda_d(\rho_c^{(I)}-\rho_c)}-\sqrt{(1-\rho_c)(1-\rho_d)}\right)^2}{\rho_d^{(I)}-\rho_d}\right\}\right\}, \tag{10}$$

IV. Multiple D2D Scenario

We assume N D2D pairs $\{1,2,\cdots,N\}$ share the same resources with one cellular link. We still use λ_c and μ_c to characterize the packet arrival and service rates of the cellular link, respectively. The packet arrival and service rates of D2D pair n ($n\in\{1,2,\cdots,N\}$) are respectively denoted by λ_n and μ_n. P_c represents the transmit power of the cellular link and P_n corresponds to D2D pair n. Let $G_n \sim \exp(1/\sigma_n^2)$ ($n\in\{1,2,\cdots,N\}$) denote the channel gain between the transmitter node of D2D pair n and its receiver while $G_c\sim\exp(1/\sigma_c^2)$ characterizes the cellular link. The channel gain from cellular transmitter to the receiver of D2D pair n is $G_{cn}\sim\exp(1/\sigma_{cn}^2)$ while $G_{nc}\sim\exp(1/\sigma_{nc}^2)$ corresponds to the channel gain between the transmitter of D2D pair n and the cellular receiver. As it is very difficult to obtain the exact characterization of the stability region with multiple interacting queues [13][14], we simplify the theoretical derivations via deducing the upper and lower bounds. Due to low-power short-distance transmission nature of D2D pairs [15], the performance of D2D link is mainly determined by the interference from the cellular link. Thus, we firstly derive the upper bound by ignoring the interference among D2D pairs.

Although the interference among D2D pairs are ignored in the upper bound, the interactions between D2D pairs and cellular link are still taken into consideration. Thus, the expressions of service rates of D2D pairs are similar to (3). Particularly, the service rate of D2D pair n is determined by

$$\mu_n=\left(1-\frac{\lambda_c}{\mu_c}\right)(1-\rho_n)+\frac{\lambda_c}{\mu_c}(1-\rho_n^{(I)}), \tag{11}$$

where ρ_n is the outage probability of D2D connection n without interference from cellular link, and $\rho_n^{(I)}$ characterizes the interference case. ρ_n and $\rho_n^{(I)}$ can be calculated through (5) and (7). The stable throughput constraints require that $\mu_n>\lambda_n$, thus, based on (11), we have $\mu_c>\frac{\lambda_c(\rho_n^{(I)}-\rho_n)}{1-\rho_n-\lambda_n}$. As there exists N D2D pairs, μ_c needs to satisfy:

$$\mu_c>\max\left\{\frac{\lambda_c(\rho_1^{(I)}-\rho_1)}{1-\rho_1-\lambda_1},\frac{\lambda_c(\rho_2^{(I)}-\rho_2)}{1-\rho_2-\lambda_2},\cdots,\frac{\lambda_c(\rho_N^{(I)}-\rho_N)}{1-\rho_N-\lambda_N}\right\}. \tag{12}$$

The cellular transmission suffers from the interference from all D2D pairs. D2D pair n either transmits or keeps silence within each TS. Thus there exists 2^N system state for each TS. We use 2^N vectors $\{\mathbf{v}_1,\mathbf{v}_2,\cdots,\mathbf{v}_{2^N}\}$ to describe different states where $\mathbf{v}_k=(v_{k,1},v_{k,2},\cdots,v_{k,N})$ ($k\in\{1,2,\cdots,2^N\}$), and

$$v_{k,n}=\begin{cases}1 & \text{D2D pair } n \text{ is transmitting}\\ 0 & \text{D2D pair } n \text{ keeps silence}\end{cases} \tag{13}$$

Hence, the service rate of the cellular link is calculated by

$$\mu_c=\sum_{k=1}^{2^N}\Pr\{\mathbf{v}_k\}(1-\rho_{\mathbf{v}_k}), \tag{14}$$

where $\Pr\{\mathbf{v}_k\}$ is the probability of scenario k and $\rho_{\mathbf{v}_k}$ is the corresponding outage probability. For D2D pair n, the probability of occupying the channel is $\Pr\{Q_n>0\}=\frac{\lambda_n}{\mu_n}$, where Q_n is the transmission queue of D2D pair n. Thus we have

$$\Pr\{\mathbf{v}_k\}=\prod_{n=1}^{N}\left|1-v_{k,n}-\frac{\lambda_n}{\mu_n}\right|. \tag{15}$$

Then we calculate $\rho_{\mathbf{v}_k}$ as

$$\rho_{\mathbf{v}_k}=\Pr\left\{B\log\left(1+\frac{P_cG_c}{\sum_{n=1}^{N}v_{k,n}P_nG_{nc}+N_0}\right)<R_c\right\}$$
$$=1-\sum_{n=1}^{N}\frac{v_{k,n}P_c\sigma_c^2(P_n\sigma_n^2)^{||\mathbf{v}_k||_1-1}}{\prod_{i=1,\, i\neq n}^{N}v_{k,i}(P_n\sigma_n^2-P_i\sigma_i^2)(\eta_cP_n\sigma_n^2+P_c\sigma_c^2)}e^{-\frac{\eta_cN_0}{P_c\sigma_c^2}}, \tag{16}$$

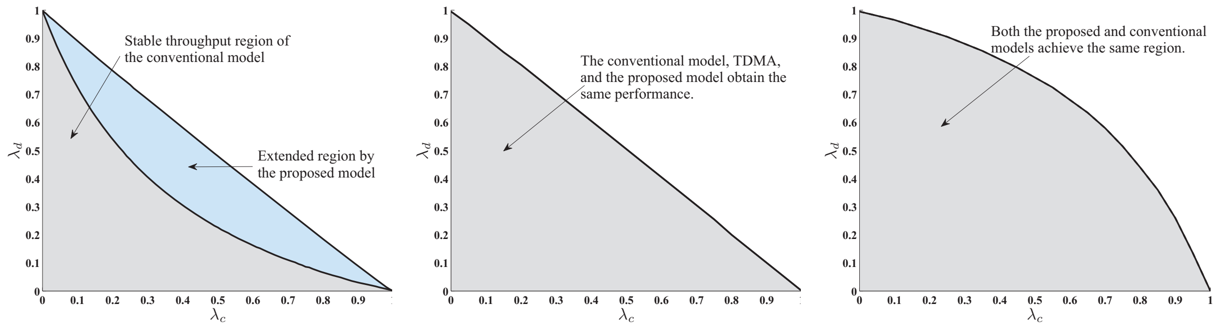
where $||\mathbf{v}_k||_1=\sum_{n=1}^{N}v_{k,n}$. Based on (15) and (16), the right hand side of (14) can be defined as a function on μ_c, denoted by $f(\mu_c)$. Thus, μ_c is the root of $f(\mu_c)-\mu_c=0$. The stable throughput constraints require that $\mu_c>\lambda_c$ and $\mu_n>\lambda_n$. For D2D pairs n, $\mu_n>\lambda_n$ is satisfied if (12) holds. Meanwhile, stable constraints also require $\mu_c>\lambda_c$. Based on the above derivations, we have the following theorem.

Theorem 2. *The upper bound of the stable throughput region $\mathcal{R}_{\text{upper}}$, when one cellular link with packet arrival rate λ_c and N D2D pairs with packet arrival rates $\{\lambda_1,\lambda_2,\cdots,\lambda_N\}$ ($N\geq 1$) share the same resources, is given as*

$$\mathcal{R}_{\text{upper}}=\left\{(\lambda_c,\lambda_1,\cdots,\lambda_N)\,\middle|\,\mu_c>\max\left\{\lambda_c,\frac{\lambda_c(\rho_1^{(I)}-\rho_1)}{1-\rho_1-\lambda_1},\frac{\lambda_c(\rho_2^{(I)}-\rho_2)}{1-\rho_2-\lambda_2},\cdots,\frac{\lambda_c(\rho_N^{(I)}-\rho_N)}{1-\rho_N-\lambda_N}\right\}\right\}, \tag{17}$$

where μ_c is the root of $f(\mu_c)-\mu_c=0$.

The lower bound of the region can also be obtained through assuming that the interference among D2D pairs always exists. The derivations are almost the same as those of the upper bound. We only need to replace noise power N_0 at the receiver of D2D pair n with $N_{0,n}=N_0+\sum_{k=1,k\neq n}^{N+1}P_kG_{kn}$. Thus, the derivation of the lower bound will not be detailed in this paper due to length limit. The result will be shown in simulations.



(a) $L \approx 80m$ (b) $L \approx 100m$ (c) $L \approx 120m$

Fig. 2. The stable throughput regions of single D2D pair scenarios. "L" stands for the distance between the D2D link and the cellular link.

V. Numerical Results

We compare the proposed model with the conventional one and the TDMA transmissions. The "conventional model" refers to the common assumptions in existing works [2-6], where they only considered Case 2 (the worst case) when calculating SINRs or data rates. In TDMA, the same TSs will not be allocated to more than one connection, i.e., orthogonal transmissions without interference. Path-loss exponent $\alpha = 4$. The power constraint for the cellular link is 23dbm and 17dbm for D2D links. Bandwidth is 180kHz and the outage threshold rate of each link is 5 bit/s/Hz. The distance between the BS and the CUE is 100m and the distance of D2D link is 20m.

Firstly, we consider the single D2D pair scenario, where downlink resources are reused. The stable throughput regions in different scenarios are given in Fig. 2. We change the distances between the cellular link and the D2D pair L. The bound line in each figure is the best achievable region bound when adjusting the power of each transmitter. The TDMA bound with two-user case is known as a straight line $\lambda_c + \lambda_d \approx 1$. Thus, for simplification, we do not plot its curve in Fig. 2(a) and 2(c). It can be seen from Fig. 2(a) that when the distance between the two links is small, the stable throughput region of the proposed scheme contains both the grey area (the region of the conventional model) and the blue area (the extension when compared with the conventional model). With the increase of the distance between the two links, the conventional region approaches the proposed one and all of them achieve the same boundary when the conventional one reaches the TDMA region, as depicted in Fig. 2(b). After that, when the distance between the two links continues increasing, where the inter-link interference is too small to affect each other's transmissions, both the conventional region and the proposed one outperform that of TDMA, as shown in Fig. 2(c).

Then we extend our experiments to multiple D2D pairs. Since it is difficult to plot the high-dimensional regions for large N, we test the "Access Probability" behaviors by Monte Carlo simulations, where admission occurs if all the packet arrival rates are within the stable throughput region. The average packet arrival rates of D2D pairs are uniformly distributed in [0,1]. "Prop." stands for the proposed model and "Conv." is the conventional one. As shown in Fig. 4, the improvements of the proposed model become more significant with the increase of N. This is because the conventional model assumes interference within every TS. Such interference grows remarkably with the increase of the number of interactional connections. With large N, the accuracy of actual interference model plays a more significant role in determining network performance.

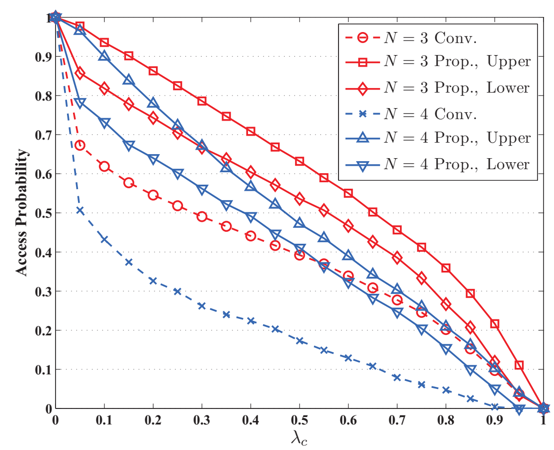


Fig. 3. Admission behaviors of multiple D2D pairs scenarios. $L_c = 100m$.

VI. Conclusion

In this paper, a new cross-layer model is established to characterize the actual inter-user interference scenarios between cellular connection and D2D links when they share the same resources. The stable throughput regions are deduced to demonstrate the behaviors of non-orthogonal transmissions among multiple interactional links. As a consequence, the proposed model outperforms both TDMA and the conventional one, enlarging the achievable throughput region by accurately characterizing the interference scenarios.

References

[1] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, et al., "Design aspects of network assisted device-to-device communications," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 170-177, 2012.

[2] H. Min, J. Lee, S. Park, and D. Hong, "Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 3995-4000, Dec. 2011.

[3] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-todevice communications underlaying cellular networks," *IEEE Trans. Commun.,* vol. 61, no. 8, pp. 3541-3551, Aug. 2013.

[4] Y. Chai, Q. Du, and P. Ren, "Partial time-frequency resource allocation for device-to-device communications underlaying cellular networks," in *Proc. IEEE ICC*, Budapest, Jun. 2013, pp. 6055-6059.

[5] D. Zhu, J. Wang, A. L. Swindlehurst, and C. Zhao, "Downlink resource reuse for device-to-device communications underlaying cellular networks," *IEEE Signal Process. Lett.,* vol. 21, no. 5, pp. 531-534, May 2014.

[6] W. Zhao, and S. Wang, "Low complexity power allocation for device-to-device communication underlaying cellular networks," in *Proc. IEEE ICC*, Sydney, NSW, Jun. 2014, pp. 5532-5537.

[7] B. Wang and K. J. R. Liu, "Advances in Cognitive Radio Networks: A Survey," *IEEE J. Sel. Topics in Signal Process.*, vol. 5, no. 1, pp. 5-23, Feb. 2011.

[8] C. X. Jiang, Y. Chen, K. J. R. Liu, and Y. Ren, "Renewal-Theoretical Dynamic Spectrum Access in Cognitive Radio Networks with Unknown Primary Behavior", *IEEE J. Sel. Areas in Comm.*, vol 31, no 3, pp. 406-416, March 2013.

[9] A. K. Sadek, K. J. R. Liu, and A. Ephremides, "Cognitive Multiple Access via Cooperation: Protocol Design and Performance Analysis," *IEEE Trans. Inf. Theory*, vol 53, no 10, pp. 3677-3696, Oct. 2007.

[10] I. Krikidis, B. Rong, and A. Ephremides, "Cooperation for multi-pleaccess channel via dynamic decode-and-forward," *IEEE Trans. Inf. Theory*, vol. 57, no. 12, pp. 7759-7770, Dec. 2011.

[11] R. Loynes, "The stability of a queue with non-interdependent interarrival and service times," *Proc. Camb. Philos. Soc.*, vol. 58, pp. 497-520, 1962.

[12] D. Bertsekas and R. Gallager, *Data Networks*, 2nd ed. Englewood Clifffs, NJ: Prentice-Hall, 1987.

[13] W. Szpankowski, "Stability conditions for some distributed systems: Buffered random access systems," *Adv. Appl. Probab.*, vol. 26, pp. 498-515, 1994.

[14] R. Rao and A. Ephremides, "On the stability of interacting queues in a multiple-access system," *IEEE Trans. Inform. Theory*, vol. 34, no. 5, pp. 918-930, Sep. 1988.

[15] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Deviceto-device communication as an underlay to LTE-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42-49, Dec. 2009.