Statistical Traffic Control for Cognitive Radio Empowered LTE-Advanced with Network MIMO

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***Abstract*—Deploying 3GPP LTE-Advanced to the ISM band resolves the deployment issue of obtaining feasible bandwidth from crowded spectrum. However, considering that wireless local area networks (WLANs) have been deployed to the ISM band, recent researches show that LTE-Advanced needs to provide communication opportunities for WLANs. Such a coexistence relies on applying the *cognitive radio technology* to LTE-Advanced. However, the *cognitive channel access* leading to severe channel availability variation obstructs quality-of-service (QoS) guarantees in LTE-Advanced. To alleviate channel availability variation, we adopt a powerful technology known as the network multiple-input-multiple-output (MIMO) and propose the statistical traffic control scheme comprising the packet transmission scheduling and the admission control for LTE-Advanced to tackle critical challenges of the packet transmission coordination and the radio resources allocation in the network MIMO. Simulations results demonstrate an effective support of voice and video transmissions, thus enabling a successful coexistence with WLANs.**

I. INTRODUCTION

TO enable ubiquitous communications with increasing demands of personal communication services, existing cellular systems (i.e., WCDMA) had shown the lack on the support of high data rates. This insufficiency consequently drives the development of advanced cellular systems such as 3GPP LTE-Advanced. However, current crowded spectrum poses an obstacle on obtaining feasible bandwidth for LTE-Advanced. Deploying LTE-Advanced to the ISM band thus emerges as a promising solution [1], [2]. Since IEEE 802.11b wireless local area networks (WLANs) are deployed to the ISM band, recent studies show that LTE-Advanced may block communications of WLANs [1], [2]. Although WLANs may also invoke interference to LTE-Advanced, low quality communications may still be available in LTE-Advanced. Therefore, for a successful coexistence, LTE-Advanced may need to provide communications opportunities for WLANs.

Due to the lack of interfaces between LTE-Advanced and WLANs, LTE-Advanced needs to "autonomously" control interference. For this purpose, the *cognitive radio* (CR) technology enabling a station to cognise and adapt to communication environments [3], [4] is well suited for LTE-Advanced to enable an autonomous interference mitigation [5], by which, stations in LTE-Advanced can suspend transmissions to provide transmission opportunities for WLANs when transmissions in WLANs are detected. However, since transmissions with timing constraints of LTE-Advanced are blocked in order to provide transmission opportunities for WLANs, such a *cognitive channel access* results in a severe variation of channel availability [6], [7] and obstruct provisioning of quality-of-service (QoS) guarantees in LTE-Advanced.

Providing QoS guarantees is the key of a successful practice of a wireless system so as LTE-Advanced. To provide QoS guarantees, the end-to-end channel availability variation shall be alleviated [8]. For this purpose, we note a powerful technology known as the network multiple-input-multiple-output (MIMO). The network MIMO is an integration of (i) coordinated multi-point (CoMP) transmissions from multiple LTE-Advanced base stations (known as eNBs) to one user equipment (UE) and (ii) cooperative relaying by leveraging multiple relay nodes (RNs) to forward the packet to the UE. By leveraging the network MIMO, packets to be transmitted to the UE are available in multiple eNBs with the facilitation of (wired) backhaul in CoMP. Therefore, multiple eNBs can transmit identical packets to the UE. In addition to the direct transmission path from each eNB to the UE, RNs also form additional relay paths. Thus, the network MIMO provides multiple paths from multiple eNBs to the UE. Each path can be single link from an eNB to the UE, or multiple links via RNs. Thus, the timing constraint is violated only if all links are unavailable in all paths. The network MIMO thus alleviates end-to-end channel availability variation to decrease the timing constraint violation probability.

Although the network MIMO is applied, it does not suggest guaranteed QoS in LTE-Advanced. To satisfy timing constraints of all packets belonging to different streams with diverse QoS characteristics and requirements, there are two critical challenges, (i) how to coordinate transmissions of packets with diverse QoS characteristics and requirements by leveraging the network MIMO, and (ii) how to determine radio resources for each stream to ensure that QoS requirements of all streams can be satisfied under any given network MIMO topologies (i.e., the number of paths to the destination and the number of links in each path). To tackle these challenges, we shall propose a statistical traffic control scheme comprising (i) a packet transmission scheduling coordinating transmissions of constant-bit-rate (CBR) and variable-bit-rate (VBR) streams, and (ii) an admission control deciding radio resources for each stream to achieve statistical QoS guarantees (i.e., the probability of timing constraint violation is bounded by a predetermined value) for LTE-Advanced.

II. SYSTEM MODEL

Consider a downlink network MIMO transmission problem in LTE-Advanced coexisting with multiple WLANs, as shown

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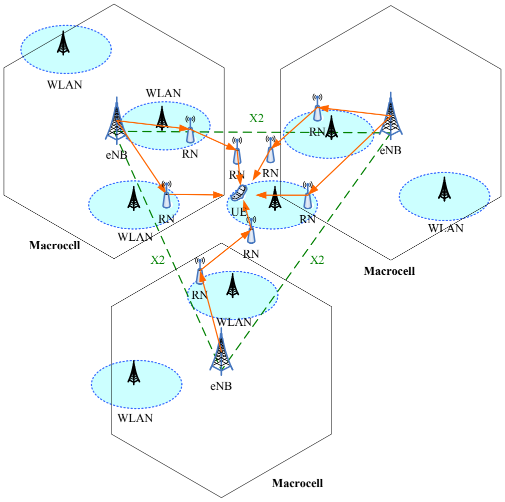

Fig. 1. Multiple eNBs can forward identical packets to the UE through direct transmissions or via relay transmissions.

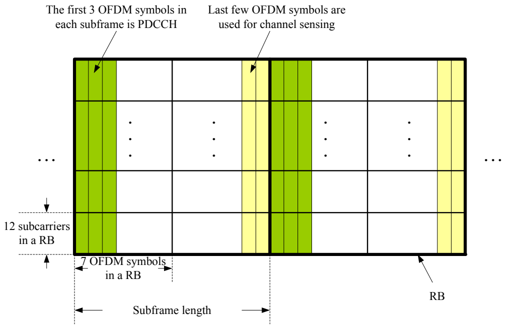

Fig. 2. The subframe structure of LTE-Advanced.

in Fig. 1. According to the network architecture of LTE-Advanced, there is an interface (known as X2) among eNBs, by which each eNB can have a copy of downlink data required to be transmitted to the UE. Multiple eNBs thus can transmit identical packets directly to the UE. In addition to the direct transmission, each eNB can leverage RNs to forward packets to the UE through two-hop or multi-hop relaying. As a result, K paths (without interference among paths via ceratin cell planning) indexed by $k = 1, \ldots, K$ can be constructed from multiple eNBs to the UE with or without relaying. Denote L_k as the number of links in the kth path indexed by $l = 1, \ldots, L_k$. The ultimate goal of the statistical traffic control is to deal with transmissions of K paths.

To provide transmission opportunities for WLANs, each eNB and RN shall be able to measure the channel to detect transmissions of WLANs. For this purpose, it is proposed to arrange few orthogonal frequency division multiplex (OFDM) symbols at the end of each subframe for channel measurements, as shown in Fig. 2. These OFDM symbols are referred as the *measurement channel*. LTE-Advanced adopts orthogonal frequency division multiple access (OFDMA). The first one to three OFDM symbols in each subframe serve as the physical downlink control channel (PDCCH) which indicates resource blocks (RBs) allocation of the following share channel (PDSCH) for data transmissions. Each eNB and RN shall suspend transmissions in the subsequent subframe if a transmission of the WLAN is detected at the measurement channel, which results in an ON-OFF channel [6] on each link. Denote probabilities of ON (available) and OFF (unavailable) state of the lth link of the kth path as $\varphi^0_{l,k}$ and $\varphi^1_{l,k}$ that can be estimated by each eNB and RN.

In this paper, two classes of streams, CBR and VBR, are considered. All packets of streams are with an identical size. A CBR stream is characterized by three parameters (λ, δ, ε), where λ is the packet arrival rate of the stream, δ is the maximum tolerable jitter, and ε is the acceptable jitter constraint violation probability. Packets of an CBR stream are generated periodically every $1/\lambda$ subframes and are stored in a ready-to-transmit (RTT) buffer of this CBR stream. Jitter is defined by the difference between the time of two successive packet departures and the time of two successive packet arrivals. CBR streams with a higher arrival rate, λ, have a higher priority. A VBR stream is characterized by four parameters (ρ, σ, d, ξ), where ρ is the average packet arrival rate, σ is the maximum burstness (the maximum number of packets in an arrival), d is the maximum tolerable delay, and ξ is the acceptable delay constraint violation probability. A VBR stream regulated by a (σ,ρ)-leaky bucket is stored in the RTT buffer of this VBR stream. VBR streams are with bulk arrivals. Data can be decoded at the destination only if entire bulk of packets are received before the expiration of d. VBR streams with a smaller d have a higher priority.

III. PACKET TRANSMISSION SCHEDULING

Due to the cognitive channel access on each link, the numbers of subframes required to forward the packet(s) from each eNB to the UE through different paths may be distinct, which obstructs sources on determining an appropriate moment for the next packet(s) transmission. If the packet(s) transmission is performed too frequently, the packet(s) may be congested on certain paths. If the packet(s) transmission is performed too rarely, radio resources may be wasted. To solve this dilemma, it is proposed that [9] the UE feedbacks a message to eNBs to indicate a successful packet(s) reception. eNBs then transmit the subsequent packet(s) upon receiving the feedback message. However, such a feedback based solution requires additional feedback time, which may harm QoS guarantees. To tackle this issue, we adopt the reservation based solution. That is, τ_c subframes are reserved for one packet transmission for each CBR stream. For each VBR stream, $\sigma_j \tau_c$ subframes are reserved for one bulk of packets for the jth VBR stream, where σ_j is the maximum burstness of the jth VBR stream. τ_c and $\sigma_j \tau_c$ are referred as the *transmission duration*. Each eNB then performs the subsequent packet(s) transmission at the end of each transmission duration. Such a packet transmission scheduling is detailed in Algorithm 1.

In Algorithm 1, τ_c is a parameter required to be appropriately designed. For this purpose, the admission control is proposed in the following section.

IV. ADMISSION CONTROL SCHEME

To provide the admission control scheme, we shall analytically derive the upper bounds of jitter and delay constraints

Algorithm 1 PACKET TRANSMISSION SCHEDULING

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Step 1 At the end of a transmission duration, eNBs first scan their RTT buffers of CBR streams according to the present priority.
Step 2 If a packet is found in the RTT buffer, all eNBs transmit at most one packet directly to the UE (if there is a direct transmission path between the eNB and the UE), or to RNs, then RNs forward this packet to the UE directly or via other RNs.
  Step 2.1 $\tau_c$ subframes are reserved for the transmission of this CBR packet. All eNBs and RNs perform channel sensing at the measurement channel of each subframe. If a transmission of the WLAN is detected by the eNB or the RN, the eNB or the RN suspends the packet transmission in the next subframe.
  Step 2.2 Otherwise, the eNB or the RN continues the packet transmission in the next subframe.
  Step 2.3 If $\tau_c$ is expired while none of $K$ paths can successfully forward the packet to the UE, the packet is discarded.
Step 3 If there is no packets found in RTT buffers of all CBR streams, eNBs then scan their RTT buffers of VBR streams according to the present priority.
Step 4 If a bulk of packets can be found in an RTT buffer (say the $j$th VBR stream), eNBs transmit all these packets in the RTT buffer to the UE according to Step 2a and Step 2b and $\sigma_j\tau_c$ subframes are reserved for the transmission of these packets.
  Step 4.1 If $\sigma_j\tau_c$ is expired while none of $K$ paths can successfully forward the bulk of packets to the UE, the bulk of packets are discarded.
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violation probabilities of CBR and VBR streams to provide constraints for QoS guarantees. When a new (CBR or VBR) stream attempts to be served, τ_c is calculated for all streams. The new stream is admitted if all constraints are satisfied. Such an admission control scheme is elaborated in the following.

A. Upper Bounds of QoS Constraints Violation Probabilities

Consider that there are n_c CBR streams indexed by $i = 1, \ldots, n_c$, and there are n_v VBR streams indexed by $j = 1, \ldots, n_v$. The present priories of CBR and VBR streams are sorted in the increasing order. That is, the first CBR stream has the highest priority among all streams. Denote (λ_i, δ_i, ε_i) as the parameters of the ith CBR stream and denote (ρ_j, σ_j, d_j, ξ_j) as the parameters of the jth VBR stream. The upper bounds of the jitter constraint violation probabilities of CBR streams are given by the following theorem.

Theorem 1. *Let*

$$\delta_i^* = \tau_c + \sum_{g=1}^{i-1} \lceil \frac{\lambda_g}{\lambda_i} \rceil \tau_c, \; i = 1, \ldots, n_c, \qquad (1)$$

where $\lceil x \rceil$ is the integer ceiling of x. If $\delta_i^* + \tau_c \leq 1/\lambda_i$ and $\delta_i^* < \delta_i$ for all i, the jitter constraint violation probability of the ith CBR stream is bounded above by $\bar{\Theta}_c/\tau_c$, where $\bar{\Theta}_c$ is the mean of Θ_c and Θ_c is the true end-to-end packet delivery time of an CBR packet by leveraging K paths.

The proof of Theorem 1 is provided in Appendix A. In Theorem 1, the true end-to-end packet delivery time of an CBR packet transmission via the kth path (denoted by Θ_c^k) is defined by the sum of the number of frames that actually spent for the packet transmission and the number of subframes that transmissions shall be suspended to deliver a CBR packet from the eNB to the UE. Therefore, Θ_c in Theorem 1 is given by $\Theta_c = \min\{\Theta_c^1, \ldots, \Theta_c^K\}$. Since an VBR stream (say the jth VBR stream) is served by utilizing remaining radio resources after serving all CBR streams and previous $j-1$ VBR streams, the maximum delay of the jth VBR stream d_j^* is influenced by all CBR streams and the maximum delays of previous $j-1$ VBR streams. Thus, a recursive form is adopted to provide the upper bounds of delay constraint violation probabilities.

Theorem 2. *Recursively define*

$$d_j^* = \frac{\Theta_v(1 + \sum_{g=1}^{j} \sigma_g + \sum_{g=1}^{j-1} \rho_g d_g^*) + \tau_c(1 + n_c)}{1 - \tau_c \sum_{i=1}^{n_c} \lambda_i - \sum_{g=1}^{j-1} \rho_g \sigma_g \tau_c} \qquad (2)$$

for $j = 1, \ldots, n_v$. If $\tau_c \sum_{i=1}^{n_c} \lambda_i + \sum_{g=1}^{j-1} \rho_g \sigma_g \tau_c < 1$, then the delay constraint violation probability of the jth VBR stream is bounded above by $\bar{\Theta}_v/\varpi_j$, where ϖ_j is given by

$$\varpi_j = \frac{d_j(1 - \tau_c \sum_{i=1}^{n_c} \lambda_i - \sum_{g=1}^{j-1} \rho_g \sigma_g \tau_c) - \tau_c(1 + n_c)}{1 + \sum_{g=1}^{j} \sigma_g + \sum_{g=1}^{j-1} \rho_g d_g^*} \qquad (3)$$

and $\bar{\Theta}_v$ is the mean of Θ_v, Θ_v is the true end-to-end packet delivery time of a bulk of VBR packets by leveraging K paths.

The proof of Theorem 2 is provided in Appendix B. In Theorem 2, the true end-to-end packet delivery time of a bulk of VBR packets via the kth path (denoted by Θ_v^k) is defined by the sum of the number of subframes that actually spent for the packets transmission and the number of subframes that transmissions shall be suspended. Therefore, Θ_v in Theorem 2 is given by $\Theta_v = \min\{\Theta_v^1, \ldots, \Theta_v^K\}$.

In above, $\bar{\Theta}_c$ and $\bar{\Theta}_v$ shall be further derived. Due to the limit on the paper length, the rest of this subsection devotes to the derivation of $\bar{\Theta}_c$, while $\bar{\Theta}_v$ can be obtained similarly. Denote $p_{k,f}$ as the probability $\Pr\{\Theta_k = f\}$. Therefore,

$$\begin{aligned}
\bar{\Theta}_c &= \mathbb{E}[\min\{\Theta_c^1, \ldots, \Theta_c^K\}] \\
&= \sum_{g=1}^{\infty} \Pr\{\min\{\Theta_c^1, \ldots, \Theta_c^K\} \geq g\} \\
&= \sum_{g=1}^{\infty} \Pr\{\Theta_c^1 \geq g, \Theta_c^2 \geq g, \ldots, \Theta_c^K \geq g\} \\
&= \sum_{g=1}^{\infty} [\sum_{f=g}^{\infty} p_{1,f} \times \ldots \times \sum_{f=g}^{\infty} p_{K,f}] \\
&= \sum_{g=1}^{\tau_c} [\sum_{f=g}^{\tau_c} p_{1,f} \times \ldots \times \sum_{f=g}^{\tau_c} p_{K,f}] \qquad (4)
\end{aligned}$$

To derive $p_{k,f}$, two conditions shall be considered: (i) The true packet delivery time of packet transmissions on the kth path exceeds τ_c with probability Φ_k, and (ii) the true packet delivery time of packet transmissions on the kth path does not exceed τ_c with probability $1 - \Phi_k$. Therefore, $p_{k,f}$ can be expressed by $p_{k,f} = \Phi_k \Upsilon(f) + (1 - \Phi_k)\Gamma(k, f)$. For the condition (i), since an CBR packet is only allocated by τ_c subframes, if the packet transmission violates the jitter constraint, then $f = \tau_c$ and $p_{k,f} = 1$. Thus, $\Upsilon(f)$ is

$$\Upsilon(f) = \begin{cases} 1, & \text{if } f = \tau_c, \\ 0, & \text{otherwise.} \end{cases} \qquad (5)$$

For the condition (ii), denote $S_{l,k}$ as the number of subframes to deliver an CBR packet through the lth link of the kth path (the number of subframes that transmissions shall be suspended is not counted). As a result, it at least requires $\sum_{l=1}^{L_k} S_{l,k}$ subframes to deliver the packet via the kth path with L_k links. Therefore, $p_{k,f} = 0$ if $f < \sum_{l=1}^{L_k} S_{l,k}$ and $p_{k,f} = 0$ if $f > \tau_c$. If $\sum_{l=1}^{L_k} S_{l,k} \leq f \leq \tau_c$, $\Pr\{\Theta_k = f | \sum_{l=1}^{L_k} S_{l,k} \leq f \leq \tau_c\}$ is

$$\begin{aligned} \Omega_k &= \prod_{l=1}^{L_k}\{ \sum_{r_{l,k}=0}^{f-\sum_{l=1}^{L_k} S_{l,k} - r_{l-1,k}} \left(\begin{array}{c} S_{l,k} - 1 - r_{l,k} \\ r_{l,k} \end{array} \right) \\ &\cdot \quad (\varphi_{l,k}^1)^{r_{l,k}} (\varphi_{l,k}^0)^{S_{l,k}} \}. \end{aligned} \tag{6}$$

Therefore, $\Gamma(k, f)$ can be expressed as

$$\Gamma(k,f) = \left\{ \begin{array}{ll} \Omega_k, & \text{if } \sum_{l=1}^{L_k} S_{l,k} \leq f \leq \tau_c, \\ 0, & \text{otherwise.} \end{array} \right. \tag{7}$$

Finally, the probability Φ_k is given by $\Phi_k = \Phi_{1,k} + \sum_{f=1}^{L_k-1} (\prod_{g=1}^{f} (1 - \Phi_{g,k})) \Phi_{f+1,k}$, where $\Phi_{l,k}$ is the probability that the packet transmission on the lth link of the kth path violates the maximum tolerable jitter constraint,

$$\Phi_{l,k} = \sum_{r=\tau_{l,k}^{'} - S_{l,k}+1}^{\tau_{l,k}^{'}} \left(\begin{array}{c} \tau_{l,k}^{'} \\ r \end{array} \right) (\varphi_{l,k}^1)^r (\varphi_{l,k}^0)^{\tau_{l,k}^{'} - r} \tag{8}$$

where $\tau_{l,k}^{'}$ is the number of residue subframes before that τ_c is expired. Thus, $\bar{\Theta}_c$ can be obtained by (4)-(8).

B. Procedure of the Admission Control Scheme

To determine an appropriate τ_c for all streams, the procedure of the admission control scheme is proposed in Algorithm 2.

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Algorithm 2 ADMISSION CONTROL SCHEME
Step 1 Consider that $n_c$ and $n_v$ CBR and VBR streams are admitted in the system. When a new stream, say the $\hat{\imath}$th CBR stream, with parameters ($\lambda_{\hat{\imath}}$, $\delta_{\hat{\imath}}$, $\varepsilon_{\hat{\imath}}$) (or, a new VBR stream, say the $\hat{\jmath}$th VBR stream, with parameters ($\rho_{\hat{\jmath}}$, $\sigma_{\hat{\jmath}}$, $d_{\hat{\jmath}}$, $\xi_{\hat{\jmath}}$)) attempts to be served, $\tau_c$ for all existing streams and the new stream are determined to satisfy following constraints.
    (a) $\bar{\Theta}_c/\tau_c \leq \varepsilon_i$ for all $i$ and $\hat{\imath}$
    (b) $\bar{\Theta}_v/\varpi_j \leq \xi_j$ for all $j$ (and $\hat{\jmath}$)
    (c) $\delta_i^* + \tau_c \leq 1/\lambda_i$ and $\delta_i^* < \delta_i$ for all $i$ and $\hat{\imath}$
    (d) $\tau_c(\sum_{i=1}^{n_c} \lambda_i + \lambda_{\hat{\imath}}) + \sum_{g=1}^{j-1} \rho_g \tau_c \sigma_g < 1$ for all $j$
    (e) $\tau_c > 0$
If the new stream is VBR, constraint (d) is modified to
    $$\tau_c \sum_{i=1}^{n_c} \lambda_i + \sum_{g=1}^{j-1} \rho_g \tau_c \sigma_g < 1 \text{ for all } j \text{ and } \hat{\jmath}. \tag{9}$$
Step 2 If a feasible $\tau_c$ can be found, the new stream can be served and $n_c = n_c + 1$ (or $n_v = n_v + 1$ if the new stream is an VBR). Update $\tau_c$ to the new value.
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From constraint (c), it is known that the number of possible τ_c does not exceed $\lceil 1/\lambda_1 \rceil$. Therefore, the computational complexity of the admission control scheme can be acceptable.

V. PERFORMANCE EVALUATIONS

In this performance evaluation, system parameters of LTE-Advanced are adopted [12]. The system bandwidth is 20MHz (200 RBs in each subframe). 50 RBs in a subframe are allocated for the UE in each eNB and each RN if there are packets required to be transmitted. 16-QAM is adopted for the transmission. The subframe length is 1ms. In this simulation, the numbers of paths are 1, 3 and 5. The number of links in each path is randomly selected from $\{1, 2, 3, 4, 5\}$. Voice traffic is considered as the CBR stream and MPEG-4 traffic is considered as the VBR stream. The characteristics and requirements of CBR and VBR streams follow traffic models in [10], [11], are provided in Table I. In this simulation, 5 CBR and 5 VBR streams are considered. The jitter and delay constraint violation probabilities for CBR and VBR streams are set to 0.02 based on [10], [11].

TABLE I
QoS CHARACTERISTICS AND REQUIREMENTS OF CBR AND VBR STREAMS FOR SIMULATION (FROM [10] AND [11])

	CBR1	CBR2	CBR3	CBR4	CBR5
λ[a]	0.05	0.04	0.03	0.03	0.03
δ	20ms	25ms	30ms	30ms	30ms
ε	0.02	0.02	0.02	0.02	0.02

	Jurassic Park I (VBR1)	Star War IV (VBR2)	Star Trek (VBR3)	Die Hard III (VBR4)	Mr. Bean (VBR5)
σ	69 pkt	38 pkt	48 pkt	66 pkt	61 pkt
ρ[b]	0.037	0.0012	0.091	0.037	0.0556
d	40ms	40ms	40ms	40ms	40ms
ξ	0.02	0.02	0.02	0.02	0.02

[a] λ is in the unit if subframes/packet arrival.
[b] ρ is in the unit of subframes/packet arrival.

Table II shows the simulation results of the jitter and delay constraints violation probabilities of 5 CBR and 5 VBR streams. The results are demonstrated in the form of (jitter or delay constraints violation probability, probability of available state $\varphi_{l,k}^0$ on each link). We can observe that QoS requirements of all CBR and VBR streams are satisfied, which supports the effectiveness of the proposed statistical traffic control scheme.

VI. CONCLUSION

In this paper, the proposed statistical traffic control scheme resolves two critical challenges in LTE-Advanced. (i) The packet transmission scheduling coordinates transmissions of CBR and VBR streams by the network MIMO to alleviate the end-to-end channel availability variation. (ii) The admission control determines radio resources to ensure QoS guarantees of all admitted streams. Simulation results demonstrate smooth transmissions of voice and video streams, thus enabling a successful coexistence with WLANs.

APPENDIX A
PROOF OF THEOREM 1

Since packets of the ith CBR stream are generated periodically $1/\lambda_i$ subframes, by temporarily assuming $\Theta_c \leq \tau_c$, if we can show that the ith CBR stream has the maximum wait $\tilde{\delta}_i$, the jitter cannot be larger than $\tilde{\delta}_i$. Furthermore, since each packet of CBR streams is allocated by τ_c, if $\tilde{\delta}_i + \tau_c < 1/\lambda_i$, the packet can be delivered to the destination before the next packet arrival. We prove above arguments by induction with hypotheses: i) $\tilde{\delta}_i \leq \delta_i^*$ and ii) $\tilde{\delta}_i + \tau_c < 1/\lambda_i$. Considering the first CBR stream, the maximum wait is $\tilde{\delta}_1 = \tau_c = \delta_1^*$. To ensure the packet of the first CBR stream is delivered to the destination before the next arrival, the sufficient condition is

TABLE II
SIMULATION RESULTS OF THE PROPOSED STATISTICAL TRAFFIC CONTROL SCHEME ($\varepsilon = 0.02$ AND $\xi = 0.02$)

Stream	CBR1	CBR2	CBR3	CBR4	CBR5	VBR1	VBR2	VBR3	VBR4	VBR5
K=1	(0.001,0.9), (0.008,0.8)	(0.001,0.9), (0.008,0.8)	(0.001,0.9), (0.008,0.8)	(0.002,0.9), (0.008,0.8)	(0.002,0.9), (0.008,0.8)	(0,0.9), (0,0.8)	(0,0.9), (0,0.8)	(0,0.9), (0,0.8)	(0,0.9), (0.006,0.8)	(0,0.9), (0.007,0.8)
K=3	(0,0.9), (0,0.8), (0,0.7), (0.002,0.6), (0.007,0.5)	(0,0.9), (0,0.8), (0,0.7), (0.002,0.6), (0.007,0.5)	(0,0.9), (0,0.8), (0,0.7), (0.002,0.6), (0.007,0.5),	(0,0.9), (0,0.8), (0,0.7), (0.002,0.6), (0.007,0.5)	(0,0.9), (0,0.8), (0,0.7), (0.002,0.6), (0.007,0.5)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.007,0.5)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.007,0.5),	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.007,0.5)	(0,0.9), (0,0.8), (0,0.7), (0.001,0.6), (0.005,0.5)	(0,0.9), (0,0.8), (0,0.7), (0.002,0.6), (0.006,0.5)
K=5	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.001,0.5), (0.003,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.001,0.5), (0.004,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.001,0.5), (0.004,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.001,0.5), (0.004,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.001,0.5), (0.004,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0,0.5), (0,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0,0.5), (0,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0,0.5), (0,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.001,0.5), (0.003,0.4)	(0,0.9), (0,0.8), (0,0.7), (0,0.6), (0.001,0.5), (0.003,0.4)

For $K = 1$, QoS can be guaranteed when $\varphi^0_{l,k} \geq 0.8$. For $K = 3$ and $K = 5$, QoS can be guaranteed when $\varphi^0_{l,k} \geq 0.5$ and $\varphi^0_{l,k} \geq 0.4$, respectively.

$\tilde{\delta}_1 + \tau_c < 1/\lambda_i$, which is our assumption $\delta^*_1 + \tau_c < 1/\lambda_i$. Suppose the induction hypotheses hold up to the $i-1$th CBR stream. We argue by contraction that $\tilde{\delta}_i \leq \delta^*_i$. Suppose $\tilde{\delta}_i > \delta^*_i$, CBR streams, $g = 1, \ldots, i-1$, must be served. From the induction hypothesis ii), every packet of these $i-1$ CBR streams is served before the next packet arrival. Thus the total packets that can be served within (0,δ^*_i) for these $i-1$ CBR streams is at most $\sum_{g=1}^{i-1}\lceil \lambda_g \delta^*_i \rceil$. Therefore, the total amount of time to serve these packets is bounded above by $\sum_{g=1}^{i-1}\lceil \lambda_g \delta^*_i \rceil \tau_c + \tau_c$. Since $\delta^*_i < 1/\lambda_i$, $\sum_{g=1}^{i-1}\lceil \lambda_g \delta^*_i \rceil \tau_c + \tau_c$ is bounded above by $\sum_{g=1}^{i-1}\lceil \frac{\lambda_g}{\lambda_i} \rceil \tau_c + \tau_c = \delta^*_i$, which follows the definition of δ^*_i in (1). Therefore, paths cannot always be busy in (0,δ^*_i) and we reach a contradiction. This shows $\tilde{\delta}_i \leq \delta^*_i$ and the packets of the ith CBR stream will be transmitted before the next arrival. Above arguments are valid when $\Theta_c \leq \tau_c$. If $\Theta_c > \tau_c$, the packet transmission may violate the maximum tolerable jitter constraint. This probability is denoted by $\Pr[\Theta_c > \tau_c]$. By applying Markov inequality, the upper bound of $\Pr[\Theta_c > \tau_c]$ is $\Pr[\Theta_c > \tau_c] < \frac{\bar{\Theta}_c}{\tau_c}$.

APPENDIX B
PROOF OF THEOREM 2

Let $C_1(t_1, t_2)$ be the number of subframes that can be allocated to the first VBR stream in an interval (t_1,t_2]. From the proof of Theorem 1, the maximum number of packets from n_c CBR stream that can be served in an interval (t_1,t_2] is at most $\sum_{i=1}^{n_c}\lceil \lambda_i(t_2 - t_1) \rceil$. Applying the inequality $\lceil x \rceil \leq x + 1$ yields the bound $\sum_{i=1}^{n_c}[\lambda_i(t_2 - t_1) + 1]$. Since the proposed scheme is non-preemptive, the number of subframes that can be allocated to the first VBR stream in (t_1,t_2] is at least $t_2 - t_1 - \tau_c\{1 + \sum_{i=1}^{n_c}[\lambda_i(t_2 - t_1) + 1]\}$. Thus, $C_1(t_1, t_2) \geq [1 - \tau_c \sum_{i=1}^{n_c} \lambda_i]\,(t_2 - t_1) - \tau_c(n_c + 1)$. Note that the number of departures in (t_1,t_2] from a (σ,ρ)-leaky bucket is bounded above by $\sigma + \lceil \rho(t_2 - t_1) \rceil$. Applying $\lceil x \rceil \leq x + 1$ yields the upper bound $\sigma + \rho(t_2 - t_1) + 1$. Let $A_1(t_1, t_2)$ be the amount of work load (number of subframes required for packets that arrive at the RTT buffer) within the interval (t_1,t_2] for the first VBR stream. Then $A_1(t_1, t_2) \leq \Theta_v[\sigma_1 + \rho_1(t_2 - t_1) + 1]$. The delay of an arrival at time t is bounded above by $\inf\{d' \geq 0 : A_1(0, t) - C_1(0, t + d') \leq 0\}$. Maximizing over t, we have $d^*_1 = \sup_t \inf\{d' \geq 0 : A_1(0, t) - C_1(0, t + d') \leq 0\}$. Applying the upper constraint of $A_1(t_1, t_2)$ and the lower constraint of $C_1(t_1, t_2)$, we obtain $d^*_1 = \frac{\Theta_v(1+\sigma_1)+\tau_c(1+n_c)}{1-\tau_c \sum_{i=1}^{n_c} \lambda_i}$. If $d^*_1 > d_1$, the maximum tolerable delay constraint of the first VBR stream is violated. For the first VBR stream, $\Pr[d^*_1 > d_1]$ is $\Pr[d^*_1 > d_1] = \Pr[\frac{\Theta_v(1+\sigma_1)+\tau_c(1+n_c)}{1-\tau_c \sum_{i=1}^{n_c} \lambda_i} > d_1]$. Applying the Markov inequality, $\Pr[d^*_1 > d_1] = \Pr[\Theta_v > \varpi_1] < \frac{\bar{\Theta}_v}{\varpi_1}$, where ϖ_1 is defined in (3). This completes the argument for the first VBR stream. The argument for the jth VBR stream is essentially the same as that of the first VBR stream. However, the lower constraint required to be modified since the jth VBR stream utilizes remaining resources from all the CBR stream and the first $j-1$ VBR streams. Parallel to the argument of the first VBR stream, the maximum delay of the j VBR stream is bounded above by $\frac{\Theta_v(1+\sum_{g=1}^{j}\sigma_g+\sum_{g=1}^{j-1}\rho_g d^*_g)+\tau_c(1+n_c)}{1-\tau_c \sum_{i=1}^{n_c}\lambda_i-\sum_{g=1}^{j-1}\rho_g \tau_c \sigma_g}$. By applying the Markov inequality, the probability $\Pr[d^*_j > d_j]$ is bound above by $\Pr[d^*_j > d_j] = \Pr[\Theta_v > \varpi_j] < \frac{\bar{\Theta}_v}{\varpi_j}$.

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