Performance Guaranteed Statistical Traffic Control in Cognitive Cellular Networks

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Abstract—**To deploy cellular networks, crowded spectrum leads to compact arrangements of frequency bands among wireless/cellular networks resulting in unsolvable interference in Layer 1. For circumstances without centralized coordinations, the cognitive radio (CR) as the most promising technology for interference avoidance, however, can only be supported by cellular networks in limited functionalities of interference detection and *opportunistic channel access* under the concerns of unreliability in operations and potential system overheads, which may harm the most important quality-of-service (QoS) guarantees. Considering the power of multicell cooperated multipath (MCM) technology on enhancing QoS, the critical challenge lies in an effective control of packet transmissions, radio resources, and call admission from Layer 1 to Layer 3. To merge merits of CR and MCM, we propose the statistical traffic control (STC), under which, each packet of constant bit rate (CBR) and variable bit rate (VBR) sources is transmitted through all available paths in MCM. Deriving sufficient conditions for QoS guarantees, the time domain radio resource is optimized. By evaluating performance on voice and video transmissions, we demonstrate the effectiveness of the STC to practice cognitive cellular networks.**

I. INTRODUCTION

Unremittingly increasing demands on wireless services drive a fast evolution of cellular networks to support higher data rates, a larger amount of wireless users and higher mobility. However, the crowded spectrum only leaves very limited room to accommodate faster and wider deployment of cellular networks. This obstacle results in an overlapped or compact arrangement of operating (frequency) bands among wireless/cellular networks. A practical example is the 2400-2483.5 MHz ISM band utilized by both WiFi and Bluetooth, which is very close to Band-40 of 3GPP LTE-Advanced ranging from 2300-2400 MHz. Due to the imperfect transceiver components, the compactly adjacent or overlapped operating bands may introduce severe inter-system interference not only among wireless stations [1] but also within a device with multiple wireless technologies (i.e., the well known in-device coexistence, IDC, interference [2]), which immensely perplexes system and device designs. From investigations of 3GPP [2], it has been shown that using state-of-the-art RF filters does not provide sufficient rejection of interference from adjacent frequencies. As a result, to eliminate inter-system interference, avoiding simultaneous transmissions/receptions of more than one wireless systems has been shown as a practical solution [1]. For this purpose under a critical constraint without coordinations among wireless systems, the cognitive radio (CR) technology enabling a station to autonomously cognise and adapt to communications environments so as to achieve the optimum overall network performance has been regarded as a highly potential solution to state-of-the-art cellular networks to dynamically determine the optimum communication strategy [3]. In recent literature, sophisticated CR schemes of interference detection, heterogeneous systems identification, interference cancelation/alignmant, opportunistic medium access, and opportunistic routing are extensively studied for an intelligent device with CR capabilities, and networks formed by these intelligent devices (i.e., cognitive radio networks, CRNs). However, such a design paradigm for conventional CRNs may not be feasible for state-of-the-art cellular networks. The major concern is the potentially unreliability in CRNs and significant system impacts to cellular networks. Specifically, quality-of-service (QoS) should be guaranteed for services.

The major task of cellular networks is providing performance guaranteed services for devices in cellular networks (generally known as user equipments, UEs). That is, for timing-constrained services, packet transmissions shall not violate timing constraints. To achieve this ultimate goal by leveraging the CR technology to mitigate interference from adjacent/overlapped frequencies, the major challenge lies in the *opportunistic channel access* [4] for interference avoidance. That is, an opportunistic transmission proceeds only if interference is not detected; otherwise, the transmission shall be postponed. The *opportunistic channel access* may result in a severe variation on transmission availability. As a consequence, the timing constraints are violated if the channel suffers continuous interference. This issue can be resolved only with facilitation of additional technologies. In recent research [5], it is suggested that timing constraint violations can be alleviated by transmitting identical packets via multiple (transmission) paths. By such diversity, the timing constraint is violated only if none of paths can successfully deliver the packet without constraint violations, thus the performance is enhanced. In cellular networks, multipath transmission can be supported by the aid of recent innovation of coordinated multi-point (CoMP) transmission/reception and multicell cooperative relay, the critical issue for a successful performance guarantee lies in the *time-spatial tradeoff*, in multipath transmission. That is, adopting a large number of paths to transmit identical packets could significantly alleviate timing constraint violations, it also results in unnecessary resource wastes in the spatial domain. This issue turns even more challenging as heterogeneous traffic types (traffic streams with different characteristics, generation patterns and timing constraints) are taken into considerations, and is infeasible to be resolved by one-shot optimization, as the problem is typically not in a specific form (e.g., convexity).

To tackle this issue by exploiting technical merits of both CR and multicell cooperated multipath (MCM) technologies, we shall propose a novel design paradigm of a transport layer traffic control to optimally manage packet transmissions and radio resources from Layer 1 to Layer 3. In this paradigm, all available paths are exploited to transmit an identical packet of a timing-constrained service, based on one critical reasons. For timing-constrained services, avoiding timing constraint violation by the merit of multipath diversity has a higher priority than enhancing data rates by multiplexing. By such a design, the *time-spatial tradeoff* can be solved if the time domain resource is effectively managed.

To provide performance guaranteed services for UEs with given limited CR functionalities, we propose a statistical traffic control (STC) for cellular networks with timing-constraint traffic sources of constant bit rate (CBR) and variable bit rate (VBR). The proposed STC is composed of two key components: (i) A congestion avoidance (CA) transmission scheme leverages all available paths for transmitting identical packets of CBR and VBR sources.We derive sufficient conditions such that all CBR sources satisfy their jitter constraints and all VBR sources satisfy their delay constraints, in statistical sense (that is, the probability of timing constraint violation is bounded by a required value). By these sufficient conditions, (ii) an admission control scheme determines the time domain resource allocation such that timing constraints of all admitted CBR and VBR sources are satisfied. By adopting real traces of audio files (for CBR) and video files (for VBR), we show that the STC provides effective performance guarantees in cellular networks with the given CR functionalities to practically revolve the critical issue of crowded spectrum.

II. SYSTEM MODEL

Consider an uplink transmission problem (where information, such as packet arrival times, is distributive) in a cellular network with interference from other existing wireless systems (e.g., WiFi). There are a number of UEs in the cellular network and each UE has certain numbers of CBR, VBR and ABR sources. Therefore, without loss of generality, we can avoid the index of individual UE to consider CBR sources indexed by and VBR sources indexed by , as shown in Fig. 1. To avoid inter-system interference, simultaneous transmissions of more than one systems may not be allowed. To achieve this goal without coordinations among systems by the facilitation of the CR technology, the cellular network only supports limited CR functionalities as elaborated in the following.

A. The Given CR Functionalities in Layer 1 and Layer 2

In Layer 1, interference is detected by measuring the transmission power of other existing wireless systems. If this quantity exceeds a threshold, interference is detected. To further avoid interference, in Layer 2, the transmission on a link is postponed when interference is detected in Layer 1. Such a behavior of autonomous interference avoidance is known as the *opportunistic channel access* [4], which can be characterized by the transmission availability ( ) on each link. However, the *opportunistic channel access* results in a severe transmission availability variation, which harms QoS provisioning for packet transmissions with timing constraints. To alleviate this phenomenon, a promising solution is to leverage multipath transmissions.

B. Multicell Cooperated Multipath (MCM) Technology

To enhance the received signal strength, a recent innovation known as the CoMP transmission has been adopted in state-of-the-art cellular networks. By leveraging CoMP, a transmission from an UE can be received by multiple BSs. In addition to conventional BSs, relay stations (RSs) are also adopted to relay the transmission from an UE to a BS(s) to extend the coverage of the network. By cooperation among BSs and RSs, multiple transmission paths are formed from each UE to multiple BSs. Within each path, there can be multiple RSs forming multiple links from an UE to a BS, as shown in Fig. 1. Generally denote the number of paths in the network as and the number of links in the th path as . All links in the network suffer different level of interference and perform the *opportunistic channel access*. Consequently, denote as the transmission availability of the th link in the th path.

C. Traffic Sources

In this paper, two general classes of traffic in cellular network, CBR and VBR, are considered. All packets of these two classes of traffic are of the same size.

S1) A CBR source is characterized by three parameters (, ,), where is the packet arrival rate of the source, is the maximum tolerable jitter and is the acceptable jitter constraint violation probability. Packets of a CBR source are generated periodically every subframes and are stored in a ready-to-transmit (RTT) buffer for this CBR source. Jitter is defined as the difference between the time of two successive packet departures and the time of two successive packet arrivals. CBR sources with a higher arrival rate, , have a higher priority.

S2) A VBR source is characterized by four parameters (, , ,), where is the average packet arrival rate of the source, is the maximum burstness (the maximum number of packets in an arrival), is the maximum tolerable delay, and is the acceptable delay constraint violation probability. A VBR source regulated by a (,)-leaky bucket is stored in a RTT buffer for this VBR source. VBR sources are with bulk arrivals (that is, multiple packets from upper layers may arrive at the same time). Data is decodable at the destination only when entire bulk of packets are successfully received before the expiration of . VBR sources with a smaller have a higher priority.

III. THE CONGESTION AVOIDANCE (CA) TRANSMISSION

For CBR and VBR sources, due to the opportunistic channel access on each link, the numbers of subframes required to forward the packet(s) from an UE to BSs through different paths are different, which obstructs sources on determining an appropriate moment for the next packet(s) transmission. For CBR and VBR streams, efficiently utilizing the resource in time domain is very critical. To tackle this issue, we propose a reservation based solution. That is, for each CBR source, subframes are reserved for one packet transmission. For the th VBR stream, subframes are reserved for a bulk of packets, where is the maximum burstness of the th VBR stream. and are referred as the *transmission duration*. Each (CBR and ABR) source can proceed to the subsequent packet(s) transmission according to the priority at the end of a transmission duration. Such a design enables an effective congestion and flow control in each source.

Algorithm 1. *Congestion Avoidance (CA) Transmission*

1) Upon a new call is received by BSs (a CBR call carries (, ,) and a VBR call carries (, , ,)), priorities among sources are determined according to the rule that all CBR sources have higher priorities than those of VBR sources, and all VBR sources have higher priorities than those of ABR sources. The admission control then determines transmission moments for all admitted CBR, VBR and ABR sources according to priorities, updated for each CBR source, and for each VBR source. If the new call can be admitted, transmission moments for all admitted CBR and VBR sources are announced by BSs for all CBR and VBR sources.
    a) If the current transmission moment belongs to a CBR source, subframes are reserved for this CBR source. Within subframes, one packet is transmitted via all paths.
    b) If the current transmission moment belongs to a VBR source (say, the th VBR source), subframes are reserved for this VBR source. Within subframes, all packets in the RTT buffer of the VBR source are transmitted via all paths.
2) At each subframe, all UEs and RSs perform chennel sensing for interference detection. If interference is detected, the packet transmission is suspended at that link, as illustrated in Fig. 2. Otherwise, the packet transmission continues at that link.
3) When the next transmission moment comes, the current transmission is abandoned.

Under the proposed CA transmission scheme, in the following, we provide sufficient conditions of CBR and VBR sources for performance guarantees. Denote (, ,) as the parameters of the th CBR source and denote (, , ,) as the parameters of the th VBR source. The upper bounds of the jitter constraint violation probabilities of CBR sources are given in the following.

Definition 1. *The true end-to-end packet delivery time of a CBR packet via the th path, denoted by , is the sum of the number of subframes actually spent for the packet transmission and the number of subframes that the transmission shall be suspended, to deliver a CBR packet from the source to the destination. Consequently, the true end-to-end packet delivery time of a CBR packet by leveraging paths, denoted by , is .*

Theorem 1. *Let*

— (1)

where is the integer ceiling of . If and for all , the jitter constraint violation probability of the th CBR stream is bounded above by , where is the mean of the true end-to-end packet delivery time of a CBR packet by leveraging paths, denoted by .

Proof: Since packets of the th CBR source are generated periodically subframes, by temporarily assuming , if we can show that the th CBR source has the maximum wait , the jitter cannot be larger than . Furthermore, since each packet of CBR sources is allocated by subframes, if , the packet can be delivered to the destination before the next packet arrival. We prove above arguments by induction with hypotheses: i) and ii) . Considering the first CBR source, the maximum wait is . To ensure the packet of the first CBR source is delivered to the destination before the next arrival, the sufficient condition is , which is our assumption . Suppose the induction hypotheses hold up to the th CBR source. We argue by contradiction that . Suppose , CBR sources, , must be served. From the induction hypothesis ii), every packet of these CBR sources is served before the next packet arrival. Thus, the total packets that can be served within (0,) for these CBR sources is at most . Therefore, the total amount of time to serve these packets is bounded above by

(2)

Since , the quantity in (2) is bounded above by

— (3)

which follows the definition of in (1). Therefore, paths cannot always be busy in (0,) and we reach a contradiction. This shows and the packets of the th CBR source will be transmitted before the next arrival. Above arguments are valid under the assumption . If , the packet transmission may violate the maximum tolerable jitter constraint. This probability is denoted by . By applying the Markov inequality, we can obtain the upper bound of as

— (4)

which completes the proof of Theorem 1. ■

Similarly, we define the true end-to-end packet delivery time of a bulk of VBR packets leveraging paths, to provide the upper bounds of the delay constraint violation probabilities.

Definition 2. *The true end-to-end packet delivery time of a bulk of VBR packets via the th path, denoted by , is the sum of the number of subframes actually spent for the packets transmission and the number of subframes that transmissions shall be suspended to deliver a bulk of VBR packets from the source to the destination. Consequently, the true end-to-end packet delivery time of a bulk of VBR packets by leveraging paths, denoted by , is .*

Theorem 2. *Recursively denote*

(5)

for . If , then the delay constraint violation probability of the th VBR source is bounded above by , where is given by

(6)

Proof: Let be the number of subframes that can be allocated to the first VBR source in an interval (,]. From the proof of Theorem 1, the maximum number of packets from CBR source that can be served in an interval (,] is at most . Applying the inequality yields the bound . Since the proposed scheme is non-preemptive, the number of subframes that can be allocated to the first VBR source in (,] is at least . Thus, . Note that the number of departures in (,] from a (,)-leaky bucket is bounded above by . Applying yields the upper bound . Let be the amount of work load (number of subframes required for packets that arrive at the RTT buffer) within the interval (,] for the first VBR source. Then . The delay of an arrival at time is bounded above by . Maximizing over , we have . Applying the upper constraint of and the lower constraint of , we obtain . If , the maximum tolerable delay constraint of the first VBR source is violated. For the first VBR source, is . Applying the Markov inequality, —, where is defined in (6). This completes the argument for the first VBR source. The argument for the th VBR source is essentially the same as that of the first VBR source. However, the lower constraint required to be modified since the th VBR source utilizes remaining resources from all the CBR source and the first VBR sources. Parallel to the argument of the first VBR source, the maximum delay of the VBR source is bounded above by . By applying the Markov inequality, the probability is bound above by —. ■

In above, and shall be further derived. Due to the limit on the paper length, the rest of this subsection devotes to the derivation of , while can be obtained similarly. Denote . Therefore,

(7)

To derive , two conditions shall be considered. (i) The true packet delivery time of packet transmissions on the th path exceeds with probability , and (ii) the true packet delivery time of packet transmissions on the th path does not exceed with probability . Therefore, let . For (i), since an CBR packet is only allocated by subframes, if the packet transmission violates the jitter constraint, then and . Thus,

if (8)

For (ii), denote as the number of subframes to deliver an CBR packet through the th link of the th path (the number of subframes that transmissions shall be suspended is not counted). As a result, it at least requires subframes to deliver the packet via the th path with links. Therefore, if and if . If , is

(9)

Therefore,

if (10)

Finally, the probability is given by , where is the probability that the packet transmission on the th link of the th path violates the maximum tolerable jitter constraint,

(11)

and is the number of residue subframes before that is expired. Thus, by (7)-(11), can be obtained.

IV. ADMISSION CONTROL FOR CBR AND VBR SOURCES

By obtaining sufficient conditions of performance guarantees for CBR and VBR sources, in this section, an admission control scheme is proposed.

Algorithm 2. *Admission Control for CBR and VBR Sources*

1) Consider that CBR and VBR sources have been admitted by the network. When a new source, say the th CBR source, attempts to be served, for all admitted sources and the new source are determined to satisfy following constraints.
   - (i) for all and .
   - (ii) for all (and)
   - (iii) and for all and
   - (iv)
   - (v)

TABLE I. CHARACTERISTICS AND REQUIREMENTS OF CBR AND VBR SOURCES (FROM [6])

	CBR1	CBR2	CBR3	CBR4	CBR5
[a]	0.05	0.04	0.03	0.03	0.03
	20ms	25ms	30ms	30ms	30ms
	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)
	69 pkt	38 pkt	48 pkt	66 pkt	61 pkt
[b]	0.037	0.0012	0.091	0.037	0.0556
	40ms	40ms	40ms	40ms	40ms
	0.02	0.02	0.02	0.02	0.02

[a] is in the unit if subframes/packet arrival.

[b] is in the unit of subframes/packet arrival.

2) If the new source is VBR, (iv) is modified to

for all and (12)

3) If feasible can be found, the new source can be served and (or if the new source is an VBR). The the optimal is determined by the minimum among feasible . Update for all admitted sources to the optimum. Otherwise, the new source can not be served.

From constraint (iii), the number of possible does not exceed . Therefore, the computational complexity of the admission control is not an issue.

V. PERFORMANCE EVALUATIONS

To evaluate the performance of the proposed STC, we adopt the scenario of 3GPP LTE-Advanced coexisting with IEEE 802.11b (WiFi) as a demonstration example [1]. Due to the imperfection on Layer 1 components, a probability of that interference from WiFi to LTE-Advanced occurs the th link of the th path of LTE-Advanced, and transmissions on the link shall be suspended. In this simulation, system parameters of LTE-Advanced provided in TR36.814 are adopted. To show the capability of supporting multimedia transmissions, we consider voice for CBR sources and video (high quality MPEG4 trace file) for VBR sources. The characteristics and requirements of CBR and VBR sources follow traffic models in [6], [7] as provided in Table I. As a demonstration example, in this simulation, 5 CBR and 5 VBR sources are considered. The jitter and delay violation probabilities for CBR and VBR sources are set to 0.02, based on requirements in [6], [7].

To evaluate the efficiency of the proposed STC, a comprehensive evaluation on the number of paths needed for performance guarantees for 5 CBR and 5 VBR sources under all interference levels is provided in Fig. 2. In Fig. 2, we particularly adopt the existing scheme in LTE-Advanced as a comparison benchmark. In LTE-Advanced, the hybrid automatic repeat request (HARQ) is a mandatory scheme, by which, if packets are transmitted to one of BSs without violating the timing constraint, an acknowledgement (ACK) is transmitted to all sources. Upon receiving the ACK, the subsequent transmission proceeds according to the current priority among sources. On the other hand, as packets transmission violates timing constraints, negative ACKs (NACKs) are transmitted to sources. Upon receiving NACKS, the subsequent transmission is proceeded according to the present priority among sources. However, the HARQ scheme potentially wastes the time domain resource. As a result, to achieve QoS guarantees of 5 CBR and 5 VBR sources, the HARQ scheme requires larger numbers of paths, thus leads to a worse performance on efficiency. This result contains significant engineering insights. For cellular networks, an efficient scheme shall be able to provide effective performance guarantees with facilitation of a very limited number of paths. Results Fig. 2 show the effectiveness and the efficiency of the proposed STC to be applied to the state-of-the-art cellular network.

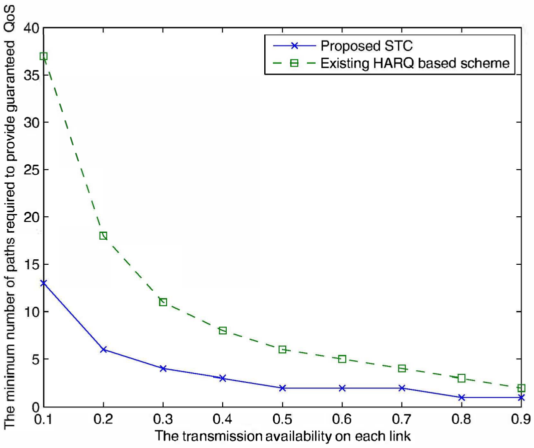

Fig. 1. The number of paths needed to provided QoS guarantees for 5 CBR and 5 VBR sources.

VI. CONCLUSION

In this paper, we overcome the most critical challenge of severe transmission availability variation due to the opportunistic channel access by leverage limited CR functionalities on interference avoidance. Our STC resolves this challenge by a novel fashion of the optimal control on packet transmissions, resource management, and call admissions, to successfully manage and integrate technical merits of CR and MCM. By our STC, we consequently enable a successful practice of CR on state-of-the-art cellular networks for the emergent issue of crowded spectrum.

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