Coexistence-Aware Scheduling for LTE and WLAN During Hard In-Device Interference

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***Abstract*—In-device interference of concurrently active radios can cause significant performance degradation in small devices such as smart phones. To avoid interference-related conflicts under challenging in-device conditions, we propose a generic radio scheduling architecture to the smart phone and small but important extensions to the LTE and WLAN protocols. To LTE, we propose scheduling duration extension to the discontinuous reception (DRX) mechanism. This provides statistically guaranteed off-durations by limiting when new data can be scheduled. To WLAN, we propose coexistence-aware delivery, which enables efficient adaptation to interference-free time periods for incoming data by adding a deadline to the delivery. Based on detailed MAC-level simulations, we show that coexistence-aware radio scheduling with the proposed protocol extensions improve significantly the LTE/WLAN coexistence under hard in-device interference compared to the current state of the art.**

I. Introduction

In this paper, we study the in-device radio coexistence problem. We focus on radio coexistence in modern hand-held devices, such as smart phones. Such devices have evolved into complex systems containing several radios, which can interfere with each other. In addition to radio interference in the air, there can be severe interference inside the devices, as the physical radio components reside very close to each other. It has been agreed that not all in-device interference cases can be eliminated feasibly with improved physical design, and therefore, there must be mechanisms supporting coexistence in the upper layers (see, *e.g.*, [1]–[3]).

There are multiple issues in the layers above the physical layer hindering coexistence. This is related to that many radio systems are complex and lack the necessary mechanisms for interference avoidance. In our research, we have concentrated on the MAC layer and time domain coexistence methods (as opposed to frequency domain coexistence methods).

A modern handset can hold a large number of radios, *e.g.*, GPS, WLAN, Bluetooth, and the 3GPP family (*e.g.*, GSM, WCDMA, LTE) radios. Often, there is no need for simultaneous use or the properties of the radios are so different that the coexistence issues are not difficult to resolve (*e.g.*, using an NFC radio while WLAN is also active). Many of the more challenging use scenarios have been sufficiently solved, including LTE VoIP phone calls with a Bluetooth headset on interfering frequency combinations [2] and using LTE during active GPS reception [4]. Other scenarios such as LTE/WLAN data offloading are not, leaving the currently available coexistence methods far from optimal.

We address the coexistence of LTE [5] and WLAN [6] on the MAC plane. In many situations, LTE and WLAN radios occupy sufficiently distant frequency bands, which allows their coexistence to be ensured with good physical design. However, there are important scenarios where this is not the case. Arguably, the most prominent hard combinations currently are WLAN on the 2.4-GHz ISM band and LTE either on band 7 or 40. On band 7, the LTE uplink (2500–2570 MHz) is so close to the ISM band that it is difficult to avoid desensitization of the WLAN receiver when LTE transmits. The case with band 40 (downlink and uplink both on 2300–2400 MHz) is even harder, as in that case the transmitters of both radios tend to desensitize the receiver of the other. It should be noted that both LTE bands are being widely adopted in important market areas: band 7 in, *e.g.*, EU, and band 40 in, *e.g.*, China. We focus on the hardest coexistence case: LTE on TDD band 40 and 2.4-GHz WLAN.

Our contribution is to propose a generic in-device architecture for interference-avoiding radio scheduling (Sec. II) with two novel coexistence enhancements for the LTE/WLAN interplay: *DRX Scheduling Duration* for LTE and *Coexistence-Aware Delivery* for WLAN (Sec. III). DRX scheduling duration is a simple yet flexible mechanism for the LTE user equipment (UE) to request traffic shaping from the base station (eNodeB) in a coexistence-friendly manner. Coexistence-aware delivery is a frame delivery mechanism that enables efficient utilization of interference-free periods and avoidance of communication during interference.

We evaluated our proposal with simulations (Sec. IV). The simulations show that the proposed mechanisms provide throughput improvements in the hard LTE-WLAN scenarios, and more importantly, they eliminate virtually all in-device interference related frame losses. The latter is crucial for energy efficiency and network-level performance.

II. Coexistence-Aware Scheduling

In coexistence-aware scheduling different radio systems attempt to synchronize their communications such that the effects of in-device interference are eliminated. Coexistence-aware scheduling is required when other means of mitigating in-device interference are not feasible. We approach the problem by describing a general method (Sec. II-A). We then describe how to apply the method for LTE-WLAN coexistence (Sec. II-B).

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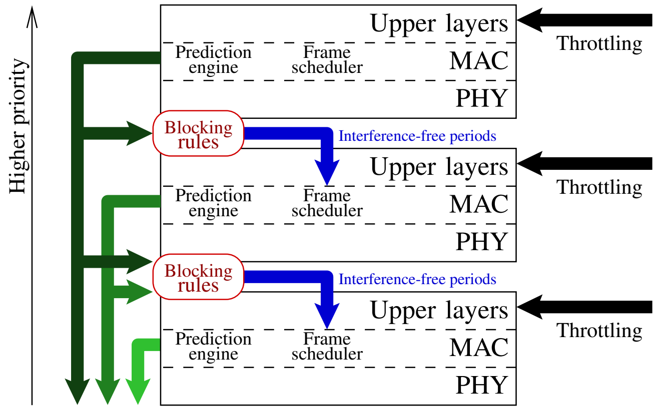

Fig. 1. Chained scheduling architecture. Higher-priority radios produce communication predictions, which are mapped by blocking rules to produce TX/RX predictions of interference-free periods. Throttling is the input parameter of the traffic shaping mechanism, which is used to maintain balance between radios.

A. *General Method*

We consider the case where a transmitter of one radio causes severe interference to the receiver of another radio. When this is the case, it is not useful to try to receive during active transmission. We assume that the conditions for interference are known and can be predicted (see, *e.g.*, [3] for a discussion).

When two radio operations interfere with each other, there is a conflict. To resolve conflicts, radios are assigned priorities and the higher-priority radio blocks the operation of the lower-priority radio. Conditions for interference and radio priorities thus produce blocking rules. The rules can be enforced by that the higher-priority radio forcibly powers down the amplifiers of the lower-priority radio in a conflict situation, for example.

Blocking rules ensure that the higher-priority radio operates well in a coexistence scenario, whereas the lower-priority radio must adapt to the interference-free time periods. For the adaptation, some exchange of information is required.

To support the lower-priority radio, the higher-priority radio maintains prediction vectors for receiver and transmitter units. The vectors contain information on known inactivity periods. With the vectors and the blocking rules, the lower-priority radio can predict the interference-free periods and adapt its radio schedule accordingly.

Whereas the lower-priority radio must adapt to the available interference-free periods, there must be a mechanism to limit the conflicting traffic of the higher-priority radio. Without limitations, or *traffic shaping*, the lower-priority radio may not receive interference-free periods at all.

This approach can be scaled to multiple concurrent radios by chaining the radios in priority order, as illustrated in Fig. 1. In the chained architecture, the interference-free periods for a radio is the intersection of interference-free periods determined by the prediction vectors of higher-priority radios.

B. *Application to LTE-WLAN Scenario*

In LTE-WLAN scenarios, the LTE user equipment (UE) is considered as the higher-priority radio. This is because of two main reasons: First, the 2.4-GHz ISM spectrum is considered free and the dedicated LTE spectrum is not. Second, the LTE MAC is less adaptable to available interference-free periods than the WLAN MAC.

LTE transmitter and receiver use can be predicted using various techniques. On TDD bands, the frame configuration, frame offset, and timing advance give an overall RX/TX pattern wherein the receptions and transmissions occur. The states of the HARQ processes can be used to produce short-term predictions. For example, when an uplink (UL) HARQ is granted, the data transmission and the acknowledgment subframe are known. However, the arrival of downlink (DL) HARQs and UL grants cannot be predicted by UE, unless scheduling patterns, UL HARQ masks, or some other extensions to the LTE standard are used [1].

Whereas HARQ states and frame configuration can be used for fine-grain short term predictions, the DRX mechanism [7] can give more coarse-grain but longer term predictions for off-periods. When the inactivity and HARQ RTT counters expire, the UE is guaranteed to sleep until the next DRX cycle, expect for the possible UE-originated scheduling requests (SR). Usually, SRs can be transmitted only in specific subframes based on the physical uplink control channel (PUCCH) allocation. The UE may send an SR only if there are data in the transmission buffers. Naturally, the buffer status is available for the prediction of SRs.

LTE DL prediction can be separated into prediction of the control and data regions. In a DL subframe, the control region utilizes the first 1–3 OFDM symbols and the data region the rest of the total 12–14 symbols of the 1-ms subframe. The special (S) subframe can be considered as a DL subframe with a truncated data region. Therefore, if it is known that the control region is used and the data region is not, there is a 0.75-ms interference-free period for the transmitters of the other radios.

After the control region of LTE subframe n has been decoded, the UL timing can be predicted precisely up to subframe $n + 4$ provided that the SRs can be predicted. In practice, after taking decoding delays and the timing advance into account, the LTE UL should be predictable always at least 2 ms in advance. When the DRX enters off-cycle, there can be tens of milliseconds of predictable inactivity.

In WLAN, data transmissions generally require that neither the transmitter nor the receiver are blocked, as both are required in close succession when sending or receiving data. For adaptation to available interference-free periods, the power save mode is the preferred choice. This is because in power save mode, the WLAN station (STA) initiates almost all communication transactions with the access point (AP), the beacons being the notable exception.

When there is a need to initiate a communication transaction, LTE prediction vectors can be used to determine the interference-free periods. This is done by applying the prediction vectors with the blocking rules.

The exploitation of an interference-free period is straightforward. When initiating a communication transaction, the

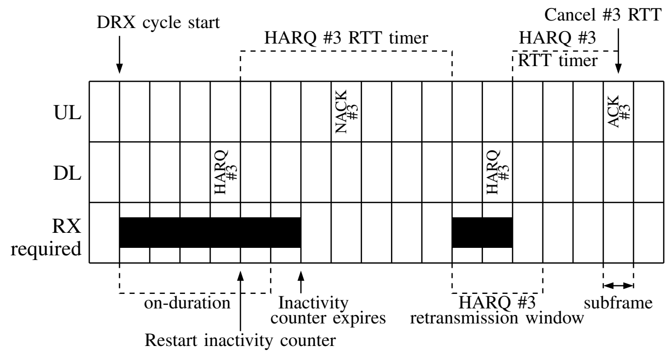

Fig. 2. DRX mechanism with on-duration, inactivity timer, HARQ RTT, and HARQ retransmission timer and their relation to the receiver active time. In this example, on-duration is configured for 5 subframes, in-activity for 2 subframes, and HARQ retransmission window as 3 subframes.

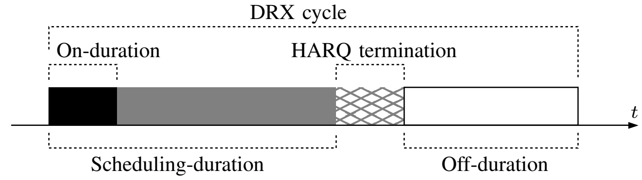

Fig. 3. Traffic shaping by DRX scheduling duration. New data can be scheduled only during on-duration and scheduling-duration. This provides statistically guaranteed interference-free off-duration for other radios to use.

transaction size including the contention window is estimated. Then, after the carrier is no longer sensed, the remaining interference-free period is determined. If the transaction can fit into the interference-free period, contention is entered. Otherwise, the next interference-free period is waited for.

When there are enough and long enough predictable interference-free periods, LTE UE and WLAN STA can coexist without any data loss due to in-device interference, except the possible beacon and other broadcast frames.

III. Coexistence Enhancements

With the current LTE and WLAN protocols, there are some fundamental issues left until coexistence-aware scheduling can be successfully implemented in hard in-device interference scenarios. Addressing these requires amendments to the protocols.

The most important LTE-related issue is the duration of communication bursts. If the LTE UE blocks the communication between the WLAN STA and the WLAN AP for extended periods, the WLAN connection is likely to be severed. To limit the duration of communication bursts, we propose a simple DRX-based traffic shaping mechanism in Sec. III-A.

Assuming that the LTE traffic can be sufficiently predicted and there are enough interference-free periods, there is a specific problem with the WLAN protocol when the buffered data is fetched from the AP. With PS-Poll [6] or U-APSD [8], the main delivery mechanisms of buffered data, brief interference-free periods cannot be reliably used. This is because the duration of the communication transactions of PS-Poll or U-APSD can vary greatly. In Sec. III-B, we propose a delivery mechanism with a deadline for better coexistence.

A. DRX Scheduling Duration

The proposed DRX scheduling duration is an extension to the LTE discontinuous reception (DRX) mechanism. It provides a flexible UE-controllable traffic shaping mechanism by providing restrictions to the eNodeB scheduler.

The LTE DRX mechanism [7], [9] is based on a set of counters with 1-ms subframe granularity. The DRX cycle is defined by a period and an offset. Each cycle starts with an *on-duration*, which specifies the minimum active time for the receiver. In addition, there is an inactivity timer, which is restarted whenever there is new activity. The inactivity timer adapts power saving flexibly to the varying amount of LTE traffic. To ensure that DL retransmissions are received gracefully, there is a round-trip timer and a retransmission timer for each DL HARQ process. Fig. 2 illustrates the DRX mechanism.

Regarding coexistence, the main issue with the DRX mechanism is that there are no guarantees that the inactivity timer will ever expire. Therefore, there are no guarantees for interference-free periods for interfered radios. This is what the proposed DRX scheduling duration provides.

The scheduling duration mechanism defines two periods from the beginning of the DRX cycle: DL scheduling duration and UL scheduling duration. When configured, new DL HARQs can be scheduled only during the DL scheduling duration and new UL HARQs can start only during the uplink scheduling duration. The DRX inactivity timer is forced to expire whenever neither of the scheduling durations are not active.

During peak loads, the scheduling duration mechanism provides traffic shaping as illustrated in Fig. 3. After the scheduling duration is expired, there is an indeterminate period when the HARQ processes are terminated. The period length depends on whether the HARQ processes require retransmissions. After the HARQ termination period, there is an off-period for other radios with statistical guarantees. However, during light loads, the inactivity timer may expire before the scheduling durations, allowing the off-duration to begin as early as with the conventional DRX mechanism.

The configuration of DL and UL scheduling durations is requested by the UE and authoritatively confirmed by the eNodeB. The rationale is that the UE knows best the transmit pressures of its radios and that the eNodeB needs to validate that the durations are in accord with its network environment. The eNodeB-confirmed values may differ from the requested values in, *e.g.*, enforcing some minimum values for the durations.

B. Coexistence-Aware Delivery

For efficient utilization of interference-free periods, the STA must be able to initiate frame transfers to interference-free periods and prevent transfers outside these safe periods. For sent data frames, the STA has always this control. Buffering

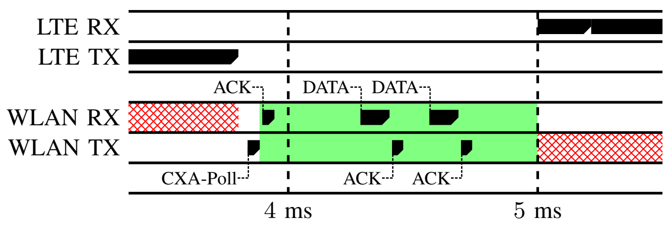

Fig. 4. CXA-Poll operation. When the interference (red crossing) ends, a CXA-Poll frame with the interference-free period (green area) information is sent to the access point. The access point replies with data frames that fit completely inside the opportunity with their accompanied ACKs.

at AP can be used to provide this control for received data frames.

Buffering at AP is ordinarily used when the STA is in power save mode. The STA uses PS-Poll frames or the U-APSD process to fetch buffered data frames from the AP. This enables the STA to have control of when the delivery of queued frames is initiated. However, the duration of the PS-Poll transaction or U-APSD delivery process is non-deterministic.

For utilizing interference-free periods, the non-deterministic duration poses a problem. The duration of the delivery must be somehow estimated when deciding whether or not to initiate the delivery. Overestimation of the duration leads to missed opportunities, while underestimation leads to the delivery to overlap with interference.

The proposed coexistence-aware delivery provides deterministic upper bound to the duration of the delivery. It is initiated by a CXA-Poll frame, which contains an explicit deadline to the delivery. Once the AP receives a CXA-Poll frame, it starts sending buffered data frames. The AP must ensure that each data frame with the corresponding acknowledgment (ACK) frame have time to be transferred before the delivery deadline. If not, sending is postponed. As the ACK frame has a constant size and it is transferred after a constant interval after the data frame, the AP can accurately estimate the upper bound for each data frame transaction. The delivery is terminated when either the frame buffer is empty or the deadline is reached.

Fig. 4 illustrates coexistence-aware delivery. When the STA has an interference-free period, it sends a CXA-Poll frame to the AP. The delivery deadline is set to the end of the interference-free period. In this example, the AP replies with two data frames that fit to the delivery window.

IV. Experiment

In this section, we analyze the LTE-WLAN coexistence mechanisms under hard in-device interference conditions. We used a simulator designed specifically for study of radio coexistence scenarios with different protocols and their extensions. The simulator models LTE UE↔eNodeB and WLAN STA↔AP MAC-level data transmissions in detail. We used attainable throughput and packet loss rate as the performance measures in a single network user setup.

As the reference configuration, we chose LTE band 40 and WLAN channel 1 setup, details are found in Table I for LTE and in Table II for WLAN, respectively. We assume priority setup as described in Sec. II-B: LTE transmission blocks WLAN reception and LTE reception prevents WLAN transmission. As interference of LTE transmission is induced in the WLAN receiver, the interference is detected in carrier sensing.

TABLE I
LTE Model Parameters

UE category	3
Frequency band	40 (2300–2400 MHz)
Bandwidth	20 MHz
TDD frame configuration	1
Timing advance	10 µs (≈ 3 km)
HARQ success prob.	0.95
DL ACKs	bundled
Symbols/subframe	14
DwPTS/Guard/UpPTS	12/1/1
Control region	3 symbols
DRX cycle	off/40 (default)/80
DRX on/inactivity/retransm.	5/5/1

TABLE II
WLAN Model Parameters

Protocol	802.11n, 2x2 MIMO RX
Band	2.4 GHz ISM
Bandwidth	20 MHz
Channel	1 (2402–2422 MHz)
Mode	Infrastructure, power save
Frame aggregation	disabled
Guard interval	800 ns
Rate selector	Minstrel
Frame SDU size	1500

The simulated LTE UE updates the prediction vectors once per subframe. The simulated WLAN STA is capable of taking advantage of the predicted interference-free periods using the mechanisms described in Sec. II-B.

We examined WLAN adaptation with the following cases:

1) Unmanaged LTE-WLAN coexistence vs. prediction-based adaptation with three subcases:
   - 1a) Unmanaged PS-Poll vs. prediction-based CXA-Poll
   - 1b) The effect of DRX cycle 40/80 for CXA-Poll
   - 1c) The effect of transmit rate to frame loss rate in unmanaged WLAN
2) Regular PS-Poll vs. CXA-Poll, both with prediction

We also examined alternative LTE traffic shapers:

3) Measurement gap as the LTE traffic shaping mechanism
4) DL scheduling masks and UL HARQ masks as the LTE traffic shaping mechanisms. Patterns are listed in Table III.

For each case, the workload consisted of received frames for WLAN and combined DL/UL for LTE with maximum load for both radios. For comparable results, we used immediate response models for both PS-Poll and CXA-Poll, and single reply for CXA-Poll. For PS-Poll, we required at least 3 ms interference-free period. For CXA-Poll, the smallest attempted period was 0.5 ms, except in the tight CXA-Poll (case 1a), even 0.3 ms interference-free periods were attempted. In cases

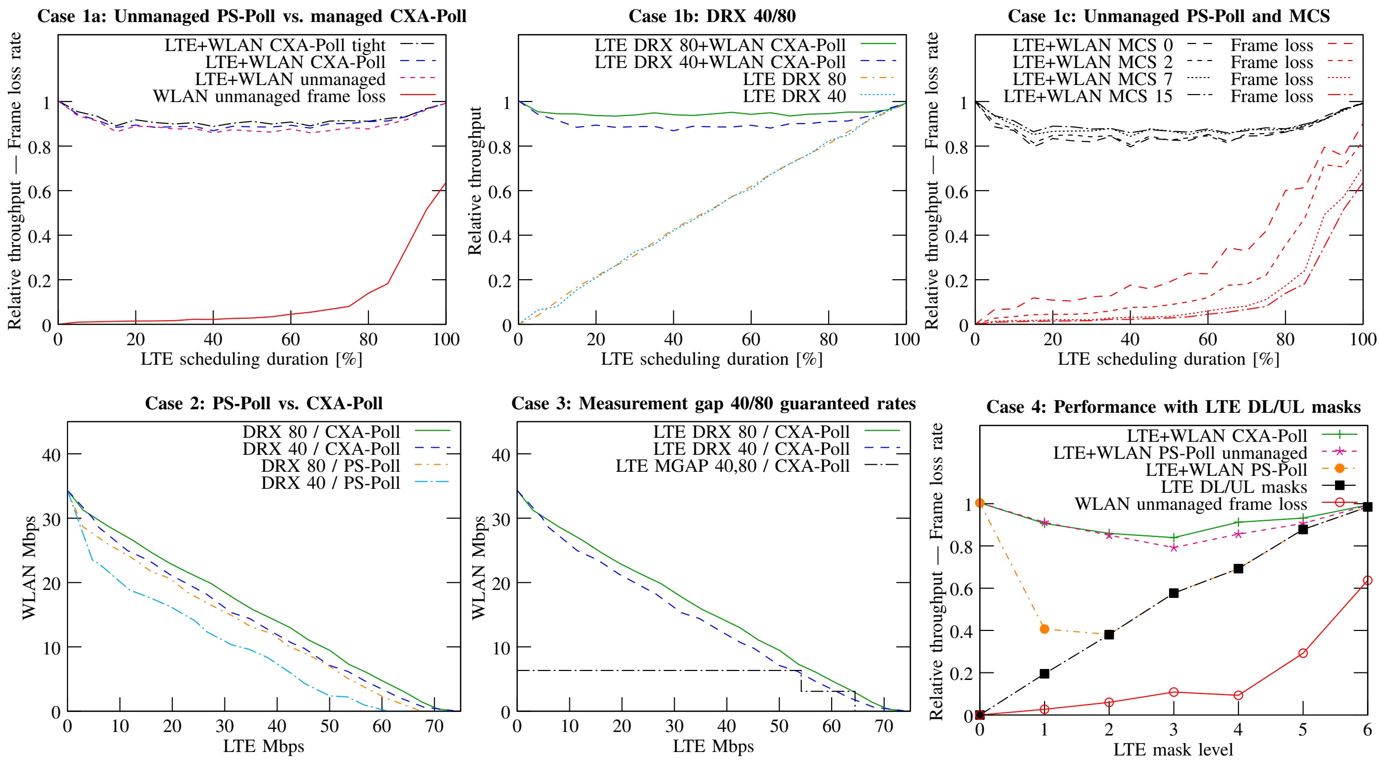

Fig. 5. Performance result figures for the experiment. Frame loss rates for coexistence-aware managed WLANs are not reported, because frames were not lost (except occasional beacon frames). In cases 1–2, LTE traffic was shaped using the proposed DRX scheduling duration counters. In case 4, DL scheduling masks and UL HARQ masks were used, instead. The relative performances used scale such that 1 is the maximum throughput without in-device interference.

TABLE III
LTE Mask Patterns for Case 4

Subframe	0	1	2	3	4	5	6	7	8	9
Level 0										
Level 1				U						D
Level 2			U	U			S			D
Level 3			U	U	D		S		U	D
Level 4			U	U	D	D	S		U	D
Level 5		S	U	U	D	D	S	U	U	D
Level 6	D	S	U	U	D	D	S	U	U	D

1 and 2, LTE is shaped with DRX scheduling duration with 5–100% range and with LTE completely disabled.

Fig. 5 summarizes the results. In overall, the combined LTE-WLAN performance was mostly unaffected by the choice of unmanaged coexistence or prediction-based CXA-Poll. The unmanaged coexistence performs well because of the CSMA-CA mechanism of the WLAN protocol.

However, in the unmanaged coexistence mode, the WLAN frame loss rate grows significantly as the LTE load increases. This is especially true when the WLAN radio is unable to use the highest bitrates, as seen in Fig. 5:1c. In prediction-based managed coexistence, the WLAN frames are never lost due to in-device interference, except occasional beacon frames, which have no effect in maximum throughput performance.

There is a bigger impact on performance in whether PS-Poll or CXA-Poll is used in managed coexistence. When PS-Poll is used, relatively conservative estimate on the duration of PS-Poll—Data—ACK transaction should be used if frame losses are to be minimized. Fig. 5:2 shows the performance impact. The conservative estimation prevents exploiting the end of the DRX off-cycles and the smaller interference-free periods during HARQ termination after scheduling duration.

The effect of DRX cycle length had a small effect on combined performance. As expected, the longer cycle was more efficient (Fig. 5:1b and Fig. 5:2), as the overheads related to DRX cycle are less frequent.

LTE measurement gaps have been considered as a coexistence mechanism. Unless enhanced, they are inflexible in terms of traffic balancing (Fig. 5:3). Non-trivial changes would be required for support of variable-sized gaps, as HARQ processes are not suspended during gaps [10].

Case 4 in our experiment examined DL scheduling masks and UL HARQ masks as the LTE traffic shaping mechanisms (Fig. 5:4). The masking mechanism is seemingly attractive in that it is easy to implement and that there is no inherent overhead as opposed to the DRX mechanism; uplink HARQs are acknowledged during downlink HARQ transmissions and vice versa. However, the masks are problematic in three ways. First, the mechanism is less flexible than DRX when the load is variable. Second, the interference-free periods for WLAN are relatively small, preventing the conservative PS-Poll working at mask level 2 and above, as they lack 3-ms interference-free slots. And finally, the inter-radio balancing is much more coarse-grained.

Of the WLAN scheduling mechanisms examined, the prediction-based managed coexistence showed clear benefits in being able to eliminate all interference-related frame losses except the occasional beacon frames. The performance of the managed mode with CXA-Poll was slightly better than regular PS-Poll, whereas the managed mode with PS-Poll performance degraded as it is less efficient in exploiting interference-free periods. Of the LTE traffic shaping mechanisms, the DRX-based scheduling duration mechanism showed flexibility for balancing LTE and WLAN traffic and providing usable interference-free periods for unmanaged PS-Poll, managed PS-Poll, and managed CXA-Poll.

V. Conclusion

Hand-held devices are rapidly evolving into systems supporting simultaneous use of multiple radios. In addition to this, the radio operating environment of the devices and the related band structure is becoming more confined as we approach the era of cognitive radios. This development calls for efficient mechanisms for coping with the in-device interference between the radios.

We studied coexistence mechanisms for LTE and WLAN. We proposed a generic coexistence-aware radio scheduling architecture and two specific enhancements for LTE and WLAN: *DRX Scheduling Duration* provides flexible means to shape the LTE traffic in a coexistence-friendly manner for WLAN. *Coexistence-Aware Delivery* enhances WLAN to enable reliable and efficient exploitation of interference-free periods. The simulations show that using the proposed enhancements, LTE and WLAN can coexist under hard in-device interference conditions, and more importantly, they show that frame losses due to interference can be virtually eliminated.

In addition to improving performance, the proposed mechanisms can be co-used to support concurrent radio resource sharing on hand-held devices [11], as they can be used to eliminate communication overlaps in time domain. Considering future research, we see that mechanisms of this kind are required for cognitive radios with smart, interference-avoiding spectrum use.

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