# In-device Coexistence Interference Evaluation and Detection in LTE-A System

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***Abstract*—In this paper, the in-device coexistence (IDC) interference detection is discussed for the user equipment (UE) with collocated long-term evolution (LTE) radio and WiFi radio. First, the comprehensive analysis is carried out to derive that the LTE transmission failure caused by the IDC interference from WiFi radio is related to the number of sub-frames overlapped with the WiFi transmission (called overlapped sub-frame). After that, consider the number of the detected overlapped sub-frames may be larger than that used to declare the serious IDC interference, an enhanced scheme is proposed to allow the enhanced NodeB (eNB) inform UE the threshold on the number of detected overlapped sub-frames. The numerical and simulation results indicate that the proposed scheme can largely reduce the detection overhead.**

## I. Introduction

With the popularity of the smart phones, it is predictable that in long term evolution (LTE) systems, the user equipment (UE) can access various networks ubiquitously by multiple collocated radios, such as LTE radio, WiFi/Bluetooth (BT) radio and global navigation satellite system (GNSS) radio. However, those radios may cause significant in-device coexistence (IDC) interference to each other [1] due to the proximity of the physical space and operating frequency. Hence, recently, 3rd Generation Partnership Project (3GPP) started a new study item (SI) aiming at the signaling and procedure for IDC interference avoidance [2]. In this SI, two types of IDC interference are considered:

- Type 1: the interference to the reception of LTE radio caused by the transmissions of other collocated radios;
- Type 2: the interference to the receptions of other collocated radios caused by the transmission of the LTE radio.

Moreover, for simplicity, this SI only studies the IDC interference avoidance between the LTE radio and one of other collocated radios.

Intuitively, the IDC interference avoidance is related to two aspects: 1) the detection of the IDC interference and 2) IDC interference avoidance solutions. Obviously, the first one is the basis of the second one. Till now, the major discussion is focused on 2) and four candidate solutions (e.g., power control, frequency division multiplexing (FDM) solution, time division multiplexing (TDM), autonomous denial) are proposed [3]. While the discussion of 1) is started from October, 2011. Thus, in this paper, we will focus on the IDC interference detection. Moreover, the considered scenario is that the collocated radio is WiFi radio and the IDC interference belongs to Type 1.

In current specification, the interference is evaluated through the periodic measurement. In particular, during each measurement period (MP), the UE measures the reference signal receiving qualitys (RSRQs) of some selected samples. Here, the sample selection is an UE implementation issue, i.e., different venders may have different sampling methods. After that, the interference is determined by averaging those RSRQ values in the MP (small averaged RSRQ value implies the large interference). However, such mechanism cannot be applied for IDC interference detection directly. According to IEEE 802.11 [4], the WiFi radio operates based on the protocol of carrier sense medium access with collision avoidance (CSMA/CA), which results in that the transmission opportunity of the collocated WiFi radio on the UE is unpredictable and randomly. In other words, the selected samples for RSRQ evaluation may not always overlap with the WiFi transmission. For example, as shown by “ Sampling in traditional measurement” in Fig. 1, only one of four selected samples in one MP overlaps with WiFi transmission. Hence, the final result derived by current measurement mechanism may not reflect the IDC interference correctly. To cope with such issue, a two-subset method was proposed in [5]. As shown by “Sampling in two-subset method” in Fig. 1, the UE divides the samples in one MP into two subsets: one includes the LTE signal samples without the WiFi signal (called Subset 1), and another contains the LTE samples with the WiFi signal (called Subset 2). Obviously, this two-subset method guarantees that all samples in Subset 2 overlap with the WiFi signal. After that, two averaged RSRQ values of the samples in both subsets can be derived, respectively. If their difference exceeds certain threshold resulting in transmission failure, the serious IDC interference can be declared. However, such method is not enough since the evaluation is only performed from the signal quality perspective. Consider the WiFi transmissions are not quite active, e.g., in each MP, Subset 2 contains one sample only. The two-subset method may declare the serious IDC interference. However, actually, such interference is endurable since the WiFi transmission is seldom and the LTE radio can recover the failure through HARQ with little performance degradation. Accordingly, detecting the IDC interference should also consider the traffic features on the LTE radio and WiFi radio, i.e., the time duration that the LTE radio or WiFi radio takes for transmission in each measurement period.

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In this paper, the IDC interference is evaluated by comprehensively analyzing the relationship between the traffic on the WiFi radio, denoted as the number of sub-frames overlapped with WiFi transmission (called overlapped sub-frame), and the downlink (DL) transmission (i.e., transmission from enhanced NodeB (eNB) to UE) failure of the LTE radio. The latter one can be regarded as an indication of IDC interference, i.e., if the failure rate of DL transmission on LTE radio exceeds a certain threshold (called the maximum endurable failure rate), the serious IDC interference can be declared. The analysis results indicate that the UE can determine the DL transmission failure rate of the LTE radio (denoted as the ratio of the number of DL sub-frames with transmission failure to the total number of DL sub-frames allocated to the LTE radio) by the number of overlapped sub-frames. In addition, the analysis presents that in some cases, the number of overlapped sub-frames significantly exceeds that corresponding to the maximum endurable failure rate. Thus, an enhanced two-subset method is proposed. In particular, the eNB notifies the number of overlapped sub-frames that the UE needs to detect, which is determined by the maximum endurable failure rate. After that, the UE declares serious IDC interference only if the number of overlapped sub-frames exceeds such value. With the proposed method, the overhead for the IDC interference detection, i.e., the number of overlapped sub-frames which needs to be detected, can be largely reduced.

The rest of this paper is organized as follows. Section II describes the system model. In Section III, a brief introduction on CSMA/CA is given. Section IV evaluates the IDC interference by considering the traffic feature. In Section V, some numerical and simulation results are presented, and an enhanced two-subset method is proposed, followed by conclusions in Section VI.

## II. System model

Consider a network consisting of the LTE cell and the WiFi cell, as shown in Fig. 2, where a tagged UE with collocated LTE radio and WiFi radio can communicate with eNB and access point (AP), simultaneously. To detect the IDC interference caused by the WiFi radio, the measurement based on the two-subset method is applied on the LTE radio, and the MP is $T_{mp}$ ms. In LTE cell, the time division duplex (TDD) mode is applied, i.e., both DL and uplink (UL) transmissions are carried out frame by frame over the same carrier. Each frame is composed of 10 sub-frames, including DL sub-frames (from eNB to UE) and UL sub-frames (from UE to eNB), each of which is 1 ms. Depending on the TDD configuration applied, the numbers of DL sub-frames and their locations are different. In WiFi cell, $N$ WiFi nodes (including the tagged UE) contend the channel according to CSMA/CA [4]. For simplicity, the full buffer model is applied to each node. The data packet has the same length, and its transmission failure is only caused by the collision with other WiFi node(s). Since the operations of the LTE radio and WiFi radio are carried out independently, it is possible that in some sub-frames, the WiFi radio is coincidentally performing UL transmission (from WiFi radio to AP). In this paper, such sub-frame is named as the overlapped sub-frame. In addition, from the perspective of the signal strength, if the overlapped sub-frame is the DL sub-frame allocated to the LTE radio, we assume the LTE data cannot be received correctly.

## III. Brief introduction of CSMA/CA

In CSMA/CA, each node has a contention window (CW), which is initially set to the minimum value $CW_{min}$ when turning on, and doubled for every transmission failure until reaching the maximum value $CW_{max}$ (=$2^m CW_{min}$). Such window will be reset to $CW_{min}$ after a successful transmission. The CW is adjusted when the node is turned on or finishes a successful/failed transmission. Whenever CW is adjusted, a back-off counter is set to a value uniformly selected between 0 and the current CW. Each node starts a back-off procedure (i.e., the back-off counter is decreased by one for every idle time slot, i.e., $T_{slot}$) only if the channel is sensed to be idle for a distributed inter-frame space (DIFS). Otherwise, the back-off counter is frozen. When a frozen back-off counter resumes the back-off procedure, it has the same value as that when it is frozen. The data transmission occurs only if the back-off counter becomes zero. To overcome the hidden terminal issue, a handshake mechanism is applied, as shown in Fig. 3. A node intending to transmit data (called sender) first sends a ready to send (RTS) packet after channel is idle for DIFS and the back-off procedure is ended (i.e., the back-off counter becomes zero). Then, the receiving node (called receiver) responses with a clear to send (CTS) packet after receiving RTS. After that, the sender starts the data packet transmission. Finally, the receiver feeds back an acknowledge (ACK). In this mechanism, each node has to send the packet excluding RTS after short inter-frame space (SIFS). If a collision (i.e., more than one node has the same back-off counters) occurs, the handshake procedure will be stopped after transmitting the RTS. Otherwise, the sender can finish the whole data transmission process[1] (i.e., the process from sending the RTS to receiving the ACK). From Fig. 3, it can be observed that except the back-off procedure, the handshake procedure should take $T_{coll}$ for collided transmission or $T_{succ}$ for successful transmission as follows:

$$T_{coll} = T_{DIFS} + T_{RTS}, \tag{1}$$

$$T_{succ} = T_{DIFS} + T_{RTS} + T_{CTS} + T_{Data} + T_{ACK} + 3T_{SIFS} \tag{2}$$

where $T_{DIFS}, T_{RTS}, T_{CTS}, T_{Data}, T_{ACK}$ and $T_{SIFS}$ represent the time durations of DIFS, RTS, CTS, Data packet, ACK and SIFS, respectively.

## IV. Evaluation of the IDC interference

In this section, the IDC interference is evaluated by considering the traffic features of LTE radio and WiFi radio. To describe the traffics during $T_{mp}$ (i.e., $T_{mp}$ sub-frames), define the number of DL sub-frames be $N_{DL}$, $U$ out of which

[1]Note that, in this paper, the transmission failure of WiFi radio is only caused by collision.

are allocated to the tagged UE on average, and the number of overlapped sub-frames be $V$. In addition, $N_{coll}$ out of $V$ overlapped sub-frames are the DL sub-frames allocated to the tagged UE. In general, a transmission failure results in a retransmission which degrades the UE performance. Thus, the ratio of $N_{coll}$ to $U$, i.e., $\frac{N_{coll}}{U}$, is a good indication of IDC interference from the perspective of traffic since it reflects the failure rate of the DL transmission of the tagged UE.

To derive $\frac{N_{coll}}{U}$, the probability of $N_{coll}$ under the condition that $U = u$ and $V = v$ is calculated first, i.e.,

$$p(N_{coll} = n_{coll}|(U = u, V = v)) = \frac{\begin{pmatrix} u \\ n_{coll} \end{pmatrix}\begin{pmatrix} T_{mp} - u \\ v - n_{coll} \end{pmatrix}}{\begin{pmatrix} T_{mp} \\ v \end{pmatrix}} \quad (3)$$

where

- $\begin{pmatrix} u \\ n_{coll} \end{pmatrix}$: the number of possible cases that $n_{coll}$ out of $u$ DL sub-frames assigned to the tagged UE are interfered by UL transmission of WiFi radio.
- $\begin{pmatrix} T_{mp} - u \\ v - n_{coll} \end{pmatrix}$: among the rest $T_{mp} - u$ sub-frames, which are not allocated to the tagged UE for DL transmission, the number of possible cases that $v - n_{coll}$ sub-frames are overlapped ones.
- $\begin{pmatrix} T_{mp} \\ v \end{pmatrix}$: the number of possible cases that $v$ out of $T_{mp}$ sub-frames are overlapped sub-frames.

After that, the mean value of $\frac{N_{coll}}{U}$, denoted as $\overline{R}$, can be calculated as

$$\begin{aligned}\overline{R} &= \sum_{u=1}^{N_{DL}} \sum_{v=0}^{T_{mp}} \sum_{n_{coll}=0}^{min\{u,v\}} \frac{n_{coll}}{u} p(N_{coll} = n_{coll}|(U = u, V = v)) \\ &\qquad * p(U = u, V = v) \\ &= \sum_{u=1}^{N_{DL}} \sum_{v=0}^{T_{mp}} \frac{v}{T_{mp}} p(U = u)p(V = v) \quad (4) \\ &= \frac{\sum_{v=0}^{T_{mp}} vp(V = v)}{T_{mp}}. \quad (5)\end{aligned}$$

In (4), $p(U = u, V = v) = p(U = u)p(V = v)$ is due to that allocating DL sub-frames to the tagged UE is independent of the appearance of the overlapped sub-frames. Interestingly, the $\overline{R}$ is just related to the average number of overlapped sub-frames, denoted as $\overline{V}$ $(= \sum_{v=0}^{T_{mp}} vp(V = v))$. The reason is that with $\overline{V}$ overlapped sub-frames on average, each LTE sub-frame has the probability of $\frac{\overline{V}}{T_{mp}}$ to overlap with the transmission of the WiFi radio. Consequently, the average failure rate over the whole duration of $T_{mp}$ is $\frac{\overline{V}}{T_{mp}}$.

Based on (5), the feature of $\overline{V}$ should be further analyzed to derive $\overline{R}$. Before the analysis, some notations are introduced according to Fig. 4. In the figure, the time line of three nodes, i.e., the tagged UE, WiFi node 1 and WiFi node 2, are illustrated. $t_s$ indicates the instant that the tagged UE finishes a transmission in WiFi cell. If such transmission is successful, it means the end of the ACK packet in Fig. 3. Otherwise, $t_s$ represents the end of the RTS packet in Fig. 3. $t_e$ indicates that the instant that the tagged UE starts a new transmission. During the period from $t_s$ to $t_e$, the tagged UE carries out the back-off procedure without transmitting any packet. Thus, such procedure can be stopped only by the data transmission of other WiFi nodes. In Fig. 4, the active slot is defined as the one followed by data transmission of one or several WiFi nodes. Otherwise, it is an idle slot. The active slot is divided into the successful slot (i.e., the slot followed by the transmission of one WiFi node) and collided slot (i.e., the slot followed by the simultaneous transmissions of more than one WiFi node). For example, in Fig. 4, two active slots are illustrated, i.e., one is the successful slot and another is the collided slot.

According to Fig. 4, for the tagged UE, define $T$, $T_x$ and $n_{OSF}$ be the period from $t_s$ to $t_e$, i.e., the duration between two successive transmission, the transmission duration of its WiFi radio, and the number of overlapped sub-frames caused by the transmission of WiFi radio, respectively. Thus, $\overline{V}$ can be approximated by[2]

$$\overline{V} = T_{mp} \frac{\overline{n_{OSF}}}{\overline{T} + \overline{T_x}} \quad (6)$$

where $\overline{T}$, $\overline{T_x}$ and $\overline{n_{OSF}}$ are the mean values of $T$, $T_x$ and $n_{OSF}$, respectively. To calculate (6), the following analysis should be focused on deriving $\overline{T}$, $\overline{T_x}$ and $\overline{n_{OSF}}$.

In Fig. 4, consider the value of the back-off counter of the tagged UE is $I$ at $t_s$. Among them, the number of successful slots and collided slots are denoted as $J$ and $K$, respectively. Thus, $T$ can be denoted as:

$$T = I * T_{slot} + K * T_{coll} + (J - K) * T_{succ} + T_{DIFS}. \quad (7)$$

Based on [6], some probabilities can be calculated as follows:

- the probability that a collision occurs, i.e., $p$, can be derived by calculating
$$p = 1 - (1 - \frac{(1 - 2p)}{1 - p - p(2p)^m} \frac{2}{CW_{min}})^{N-1}. \quad (8)$$
With $p$, the probability of $I$, i.e., $P(I = i)$, can be derived. Details can be found in [6].
- the probability that a given slot during the period from $t_s$ to $t_e$ is active, i.e., $q$, is derived by
$$q = 1 - (1 - \frac{1}{\overline{W}})^{N-1} \quad (9)$$
where $\overline{W}$ is the average CW which is calculated in [6]. Among $I$ slots, the distribution of the number of the active slots can be given as
$$P(J = j|I = i) = \begin{pmatrix} i \\ j \end{pmatrix} q^j (1 - q)^{i-j}. \quad (10)$$
- the probability that a given active slot is the collided slot, i.e., $q_c$, can be derived as
$$q_c = \frac{1 - (1 - \frac{1}{\overline{W}})^{N-1} - \frac{N-1}{\overline{W}}(1 - \frac{1}{\overline{W}})^{N-2}}{1 - (1 - \frac{1}{\overline{W}})^{N-1}}. \quad (11)$$

[2]The effectiveness of such approximation is verified in Section V.

Therefore, the distribution of the number of the collided slots among $J$ active slots is calculated as

$$P(K=k|J=j)=\left(\begin{array}{c} j \\ k \end{array}\right) q_c^k(1-q_c)^{j-k}. \tag{12}$$

By (7), (10), (12) and $P(I=i)$, the mean value of $T$ can be calculated as

$$\begin{aligned}\overline{T} &= \sum_{i=1}^{CW_{max}}\sum_{j=0}^{i}\sum_{k=0}^{j}(iT_{slot}+kT_{coll}+(j-k)T_{succ}) \\ &\qquad *p(I=i,J=j,K=k)+T_{DIFS} \\ &=(T_{slot}+qq_c(T_{coll}-T_{succ})+qT_{succ}) \\ &\qquad *\sum_{i=1}^{CW_{max}} ip(I=i)+T_{DIFS}. \end{aligned} \tag{13}$$

With the collision probability of $p$, the mean value of the data transmission duration of the tagged UE can be given by

$$\overline{T_x}=p(T_{coll}-T_{DIFS})+(1-p)(T_{succ}-T_{DIFS}). \tag{14}$$

Here, reducing $T_{DIFS}$ is resulted from that the data transmission of the tagged UE in Fig. 4 does not contain DIFS.

The following task is to compute the number of overlapped sub-frames caused by one transmission of the WiFi radio, i.e., $n_{OSF}$. Consider the example shown in Fig. 5, one transmission of the WiFi radio consumes the period of $T_{1TX}$. In particular, if the transmission is collided, $T_{1TX}=T_{coll}-T_{DIFS}$; otherwise, $T_{1TX}=T_{succ}-T_{DIFS}$. Here, reducing $T_{DIFS}$ is due to no WiFi transmission in the duration of DIFS (both $T_{coll}$ and $T_{succ}$ contain a $T_{DIFS}$). $\alpha$ is the duration from the start point of the new transmission to the end of the current sub-frame. Thus, the number of the overlapped sub-frames, i.e., $n_{1TX}$, can be determined by the value of $\alpha$ as

$$n_{1TX}=\begin{cases}\lceil T_{1TX}\rceil+1 & 0\le\alpha<T_{1TX}-\lfloor T_{1TX}\rfloor \\ \lceil T_{1TX}\rceil & T_{1TX}-\lfloor T_{1TX}\rfloor\le\alpha\le 1\end{cases} \tag{15}$$

where $\lceil X\rceil$ and $\lfloor X\rfloor$ denote the operations of ceil and floor to X, respectively. In this paper, for simplicity, the start point of one WiFi transmission is assumed to be uniformly distributed in one sub-frame. Therefore, the averaged number of the overlapped sub-frames caused by one transmission of WiFi radio can be derived by

$$\begin{aligned}\overline{n_{1TX}} &=(T_{1TX}-\lfloor T_{1TX}\rfloor)(\lceil T_{1TX}\rceil+1) \\ &\quad +[1-(T_{1TX}-\lfloor T_{1TX}\rfloor)]\lceil T_{1TX}\rceil\end{aligned} \tag{16}$$

where $(T_{1TX}-\lfloor T_{1TX}\rfloor)$ and $[1-(T_{1TX}-\lfloor T_{1TX}\rfloor)]$ denote the probabilities of $n_{1TX}=\lceil T_{1TX}\rceil+1$ and $n_{1TX}=\lceil T_{1TX}\rceil$, respectively. Depending on whether the WiFi transmission is collided or not, the mean value of $n_{OSF}$, i.e., $\overline{n_{OSF}}$, can be calculated as

$$\begin{aligned}\overline{n_{OSF}} &=p(\overline{n_{1TX}})|_{T_{1TX}=T_{coll}-T_{DIFS}} \\ &\quad +(1-p)(\overline{n_{1TX}})|_{T_{1TX}=T_{succ}-T_{DIFS}}\end{aligned} \tag{17}$$

where $(\overline{n_{1TX}})|_{T_{1TX}=T_{coll}-T_{DIFS}}$ and $(\overline{n_{1TX}})|_{T_{1TX}=T_{succ}-T_{DIFS}}$ represent that $T_{1TX}$ in (16) is $T_{coll}-T_{DIFS}$ and $T_{succ}-T_{DIFS}$, respectively. Finally, $\overline{V}$ can be derived by (6) (13), (14) and (17).

TABLE I
SOME PARAMETERS FOR WIFI CELL [8]

| | | | | | |
|---|---|---|---|---|---|
| $T_{DIFS}$ | 0.05ms | $T_{SIFS}$ | 0.01ms | $T_{slot}$ | 0.02ms |
| $T_{RTS}$ | 0.312ms | $T_{CTS}$ | 0.288ms | $T_{data}$ | 4.232ms |
| $T_{ACK}$ | 0.288ms | $CW_{min}$ | 32 | $CW_{max}$ | 1024 |

## V. RESULTS AND ENHANCEMENT

In this section, the numerical computing and simulation results are first presented. Then, an enhanced IDC detection scheme is proposed to further reduce the overhead in two-subset method.

### A. Numerical and simulation results

In this subsection, the network shown in Fig. 2 is considered. In LTE cell, TDD configuration 0 (i.e., the DL/UL setting of each sub-frame in one frame is [DL DL UL UL UL DL DL UL UL UL]) [7] is considered so that each frame contains 4 DL sub-frames. Note that the similar observation can be derived for other configurations. The MP $T_{mp}$ is set to 200ms, i.e., 200 sub-frames. In WiFi cell, the number of nodes (including WiFi radio on the tagged UE) is changed from 5 to 25 with step of 5. Other parameters for CSMA/CA scheme are listed in Table I. In the simulation, the results are averaged over 100 samples, each of which is simulated for $10^5$ seconds. Fig. 6 illustrates $\overline{R}$ and $\overline{V}$ via the number of nodes in WiFi cell. In both sub-figures, it can be observed that the analysis and simulation results are matched well. In other words, the correctness of the evaluation in Section IV is verified so that the following discussions can be carried out based on the analysis results. In addition, Fig. 6 indicates that with the decrease of the number of nodes in WiFi cell, both $\overline{R}$ and $\overline{V}$ increase largely. It is due to that when the number of WiFi nodes is large, each node has to take a long time to obtain the transmission opportunity, and thereby the number of transmissions from WiFi radio on the tagged UE decreases during $T_{mp}$. Such observation indicates that from the perspective of traffic, the WiFi radio would cause significant interference to the LTE radio in some cases (e.g., the number of WiFi nodes is small or the traffic load of the WiFi cell is high).

### B. Enhanced IDC detection scheme

Equation (5) indicates that $\overline{R}$ is only determined by $\overline{V}$. Thus, when detecting IDC interference, counting the number of overlapped sub-frames can be used so as to take the traffic into account. However, by such method, the UE has to count large number of overlapped sub-frames during each $T_{mp}$, as shown in Fig. 6. In fact, consider the UE can only endure the failure rate smaller than a threshold $\overline{R}_{thred}$, called the maximum endurable failure rate, Equation (5) shows that the UE only needs to detect $T_{mp}\overline{R}_{thred}$ overlapped sub-frames at most. For example, if $\overline{R}_{thred}$ is 0.1 and $N$ is 5, the UE only needs to detect 20 overlapped sub-frames during $T_{mp}$ on average. In other words, in some cases, the IDC interference can be detected without detecting all overlapped sub-frames. Thus, the enhanced IDC detection scheme based on the two-subset method can be designed as follows: by (5), the eNB derives the number of overlapped sub-frames that the UE needs to detect, and then notifies UE. After that, the UE declare serious IDC interference only when the number of detected overlapped sub-frames exceeds such number. According to the right-hand figure in Fig. 6, such method can reduce the number of detected overlapped sub-frames by 25 for $\overline{R}_{thred} = 0.1$ and $N = 5$ (in this case, $\overline{V}$ is almost 45), or by 13 for $\overline{R}_{thred} = 0.06$ and $N = 10$ (in this case, $\overline{V}$ is almost 25).

## VI. Conclusion

In this paper, the IDC interference between the LTE radio and WiFi radio on the UE is analyzed by taking the traffic feature into account. The results indicate that the LTE transmission failures caused by the WiFi radio increase significantly with the increase of the number of overlapped sub-frames. On the other hand, the analysis shows that for a certain transmission failure rate, the UE may not need to detect all the overlapped sub-frames. Thus, an enhanced IDC interference detection scheme is proposed. The numerical and simulation results demonstrate that the proposed scheme can largely reduce the detection cost.

## References


[1] R4-102416, In-device coexistence interference between LTE and ISM bands, Qualcomm Incorporated.
[2] RP-100671, New study item proposal: signaling and procedure for in-device coexistence interference avoidance, CMCC.
[3] 3GPP TR 36.816 v11.0.0, Study on signaling and procedure for interference avoidance for in-device coexistence.
[4] IEEE Std 802.11$^{TM}$-2007, IEEE standard for information technology –telecommunications and information exchange between systems–local and metropolitan area networks –specific requirements–part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications, 2007.
[5] R2-111299, Measurement in FDM ICO, Pantech.
[6] O. Tichoo and B. Sikdar, "Queueing analysis and delay mitigation in IEEE 802.11 random access MAC based wireless Networks", *Proc. IEEE INFOCOM 2004*, Hong Kong, Mar. 7-11, 2004.
[7] 3GPP TS 36.211, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 10)".
[8] T. Issariyakul, D. Niyato, E. Hossain, and A. Alfa, "Exact distribution of access delay in IEEE802.11 DCF MAC", *IEEE GLOBECOM 2005*, St. Louis, Mo, USA, Nov28-Dec. 02, 2005.


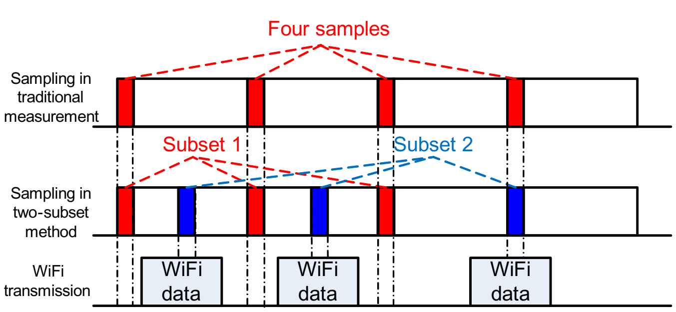


Fig. 1. Sampling method.

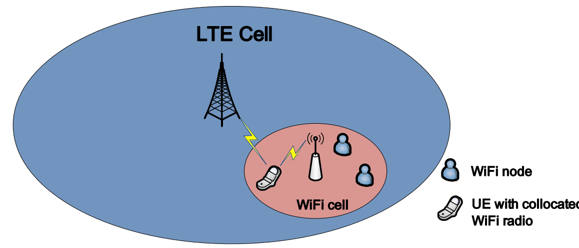


Fig. 2. System model.

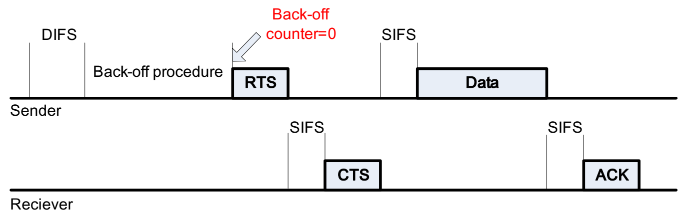


Fig. 3. Handshake mechanism in IEEE 802.11.

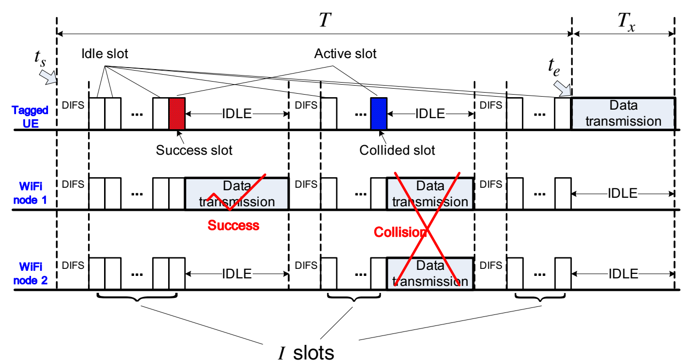


Fig. 4. Performance analysis.

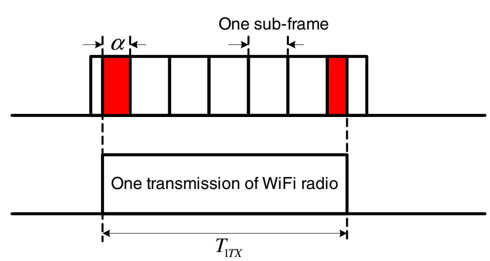


Fig. 5. The overlapped sub-frames due to one transmission of WiFi radio.

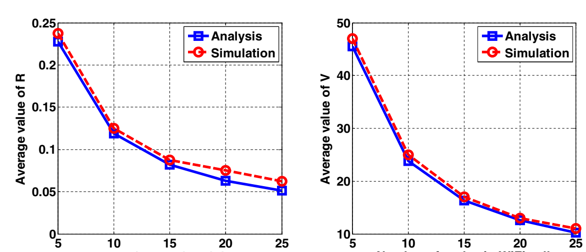


Fig. 6. $\overline{R}$ and $\overline{V}$.