

Enabling Cross-technology Communication between LTE Unlicensed and WiFi

Piotr Gawłowicz, Anatolij Zubow and Adam Wolisz
{gawlowicz, zubow, wolisz}@tkn.tu-berlin.de
Technische Universität Berlin, Germany

Abstract— LTE in Unlicensed (LTE-U) constitutes a new source of interference in the 5 GHz ISM band with a potentially strong impact on WiFi performance. Cross-technology interference and radio resource management are the best ways to assure efficient coexistence but require proper signaling channels.

We present LtFi, a system which enables to set-up a cross-technology communication between nodes of co-located LTE-U and WiFi networks. LtFi follows a two-step approach: using an innovative side channel on their air-interface LTE-U BSs are broadcasting connection and identification information to adjacent WiFi nodes, which is used in a subsequent step to create a bi-directional control channel over the wired backhaul.

The simple LtFi is fully compliant with LTE-U and works with COTS WiFi hardware. The achievable data rate on the air-interface based broadcast side channel (up to 665 bps) is sufficient for this and multiple other purposes. Experimental evaluation of a fully operational prototype has demonstrated reliable data transmission even in crowded wireless environments for LTE-U receive power levels down to -92 dBm. Moreover, system-level simulations demonstrate accurate recognition of the complete set of interfering LTE-U BSs in a typical LTE-U multi-cell environment.

Index terms— Cross-technology communication, LTE-U, WiFi, coexistence, cooperation, heterogeneous networks

I. INTRODUCTION

It is expected that the heavy usage of IEEE 802.11 (WiFi) and the proliferation of LTE in unlicensed spectrum (i.e. LTE-U [1] and LTE-LAA [2]) will result in mutual interference and thus significant performance degradation in both networks operating in 5 GHz ISM band. Although LTE and WiFi technologies have similar physical layers they are unable to decode each other's packets and have to rely on energy-based carrier sensing for actually considered – rather simplistic – co-existence. Efficient coordination assuring better performance requires, however, enabling direct cross-technology communication (CTC) between such heterogeneous systems. Unfortunately, known CTC approaches pertain to WiFi, Bluetooth and ZigBee [3], [4], [5] and therefore are not directly applicable to our LTE/WiFi scenario.

Both LTE BSs and WiFi APs are connected over the backhaul to the Internet and hence are potentially able to communicate with each other. Unfortunately, this possibility cannot be directly utilized as a discovery component for

detection and identification of co-located and interfering cells is missing. The LtFi, presented in this paper is intended to fill this gap for LTE-U. Fundamental for LtFi is the creation on a LTE-U air interface of a broadcast side channel decodable by legacy WiFi interfaces. For this purpose, LtFi exploits the option of subframe puncturing or Almost Blank Subframe (ABSF) – their relative position within LTE-U's *on-time* is used to modulate side channel data. On WiFi side, COTS hardware ability to monitor the MAC state of the WiFi NIC allows us to distinguish between WiFi and non-WiFi signals. The latter is used as input for the CTC receiver.

The so established unidirectional broadcast over-the-air CTC enables the LTE-U network to transmit arbitrary information – we use it to announce connection and identification information (e.g. public IP address of the LtFi Management Unit (LtFiMU) and Cell ID) to co-located WiFi APs. Any WiFi AP, in turn, can use this information to establish over-the-wired backhaul a secure bidirectional control channel to the LtFiMU. The so established control channel is used to build common management plane and enables collaboration between co-located LTE-U and WiFi networks.

Up to our best knowledge, LtFi is the first system that allows cross-technology communication between LTE-U and WiFi. On top of the CTC, LtFi provides also a fine-grained cross-technology proximity detection mechanism. Both these features enable advanced interference and Radio Resource Management (RRM) schemes between the considered technologies. LtFi was prototypically implemented and tested using open-source LTE implementation and COTS WiFi hardware.

II. BACKGROUND KNOWLEDGE

This section gives a brief introduction into the relevant parts of LTE-U and WiFi.

A. LTE-U

LTE-U is being specified by the LTE-U forum [1] as a cellular solution for use of unlicensed band for the downlink (DL) traffic. The LTE carrier aggregation framework supports utilization of the ISM band as a secondary cell in addition to the licensed anchor serving as the primary cell [6]. The LTE-U channel bandwidth is 20 MHz which corresponds to the smallest channel width in WiFi. LTE-U can be deployed in the USA, China and India, where LBT is not required.

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LTE-U enables coexistence with WiFi by means of duty cycling (Fig. 1) rather than LBT. Qualcomm [7] recommends that LTE-U should use period of 40, 80 or 160 ms, and limits maximal duty cycle to 50%. The LTE-U BSs actively observe the wireless channel to estimate its utilization. This estimate is used for dynamic channel selection and adaptive duty cycling. In principle, the least occupied channel is preferred. The mechanism called carrier sense adaptive transmission (CSAT) is used to adapt the duty cycle of a LTE-U BS to achieve fair radio resources sharing with neighboring WiFi and LTE nodes. This is achieved by modifying its T_{ON} and T_{OFF} values depending on the number of overheard nodes of both networks. Finally, LTE-U transmissions contain frequent gaps (so called subframe puncturing) during its *on-time*, which allow WiFi to transmit delay-sensitive data, e.g. VoIP. At least 2 ms puncturing has to be applied every 20 ms according to Qualcomm’s proposal [7].

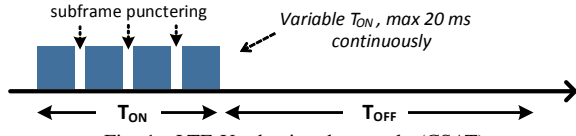


Fig. 1. LTE-U adaptive duty cycle (CSAT).

B. WiFi

In contrast to LTE-U which uses scheduled channel access WiFi stations perform random channel access using a Listen-Before-Talk (LBT) scheme (i.e. modified CSMA). While coexistence among multiple WiFi sets makes use of both virtual and physical carrier sensing, collisions with other technologies (here LTE-U) can be avoided by the energy-based carrier sensing (CS) known to be less sensitive as compared to preamble-based CS methods. The periodic (scheduled) LTE-U transmissions may impact the WiFi communication in two following ways: *i*) block medium access by triggering the Energy Detection (ED) physical CS mechanism of WiFi (less available airtime for WiFi due to contention); *ii*) corrupt packets due to co-channel interference (wasted airtime due to packet loss, i.e. a form of inter-technology hidden node). The occurrence of the first or the second effect depends on the received LTE-U signal strength at the WiFi transmitter and receiver respectively.

III. SYSTEM DESIGN

This section gives an overview of LtFi. First, we present the general architecture of our LtFi system. Then in the following sections, we give a detailed description of its components.

The most desired feature of LtFi is transparency, meaning that it should not disturb the operation of higher layers in WiFi nor LTE-U. Moreover, it should not introduce any additional overhead (like the over-the-air transmission of additional control frames or signals), but rather use the side-channel information to encode CTC data without destroying the regular LTE-U frames.

LtFi consists of two parts, namely the LtFi-Air-Interface and the over-the-wire LtFi-X2a/b-Interfaces. The first is used

for over-the-air transmission of identification parameters and data (i.e. IP address and Cell ID) from LTE-U BSs to co-located WiFi nodes. The second is a bi-directional control channel between an Access Point Management Unit (APMU) and the LTE-U network represented by LtFi Management Unit (LtFiMU). The LtFiMU is a controller of the LTE-U network and is responsible for the configuration and management of the LTE-U BSs. Fig. 2 gives a more detailed view of our system architecture. The white boxes represent the entities present in existing standards, while the gray boxes are elements of LtFi.

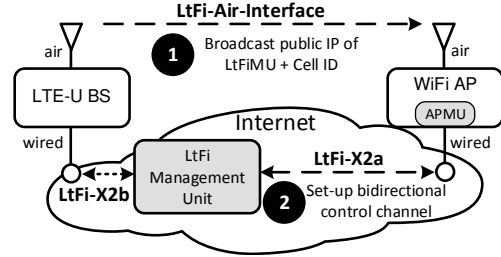


Fig. 2. Overview of the system architecture of LtFi — using the air interface a LTE-U BS transmits configuration parameters which are used to set-up an out-of-band control channels with the corresponding LtFiMU over the Internet.

A. LtFi – Air Interface

The LtFi air-interface enables a unidirectional (broadcast) over-the-air communication from LTE-U BS (sender) to WiFi nodes (receiver). Fig. 3 shows how LtFi-Air-Interface is integrated into LTE and WiFi systems respectively. Note that, as LtFi is only an add-on to existing standards, it can be easily integrated with already deployed devices by performing a software update, i.e. no protocol changes are needed.

The LtFi air-interface exploits the freedom to place the subframe puncturing into LTE-U transmission assured in the LTE-U standard. In order to transmit the CTC information, we place additional puncturing during LTE-U’s *on-time*. The puncturing has a length of 1 or 2 ms, hence the additional delay experienced by LTE-U data packets is negligible. LtFi transmitter is interfaced with the LTE-U scheduler, which is responsible for managing available wireless resources, i.e. Resource Blocks (RBs). The LtFi transmitter sends a vector $\vec{s} = [s_1, s_2, \dots, s_k]$ of CTC symbols to the eNb scheduler. A CTC symbol s_i will be represented by the relative puncturing position. The eNb scheduler takes \vec{s} into its radio resource scheduling decision, i.e. it stalls (punctures) its transmission for 1-2 ms at the time points given in the CTC symbols. Moreover, the interface between LtFi Tx and eNb scheduler is used by them to negotiate the LtFi symbol duration, the number of punctures per symbol as well as the configuration of the length of a puncture. This is needed in order to adapt to changing LTE-U traffic load (see Sec. III-E) and/or wireless channel conditions.

On the receiver side a WiFi node, typically an AP, needs to decode the LtFi CTC signal. As a direct decoding of the LTE-U frames is not possible due to incompatible physical layers, the LtFi receiver has to detect and decode radio patterns based on received signal strength (RSSI) observation. This can be achieved using spectrum scanning capabilities

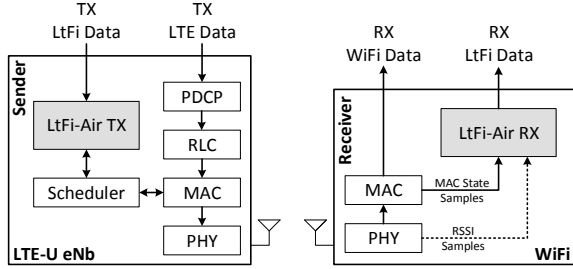


Fig. 3. Integration of LtFi-Air-Interface into LTE-U eNB and WiFi — LtFi requires an interface to the LTE-U scheduler as well as access to WiFi MAC layer information.

of WiFi NICs (e.g. Atheros). However, the receiver has to obtain and process a large amount of spectral scan data. Instead, LtFi solves this problem by utilizing the possibility to monitor the signal detection logic of modern WiFi NICs (e.g. Atheros 802.11n/ac). More specifically LtFi monitors the relative amount of time the WiFi NIC spent in the **energy detection (ED) without triggering packet reception (RX), i.e. interference (Intf) state**, which is entered on reception of a strong non-WiFi signal. As LTE-U is so far the only source of interference in the 5 GHz band, it is safe to assume LTE-U being the non-WiFi signal. In order to detect the relative position of the puncturing in the LTE-U’s *on-time*, the *Intf* state is sampled with sufficient high rate, i.e. sample duration of 0.25 ms.

B. TX/RX Chain

Beside the already mentioned (de-)modulator the TX/RX chain of LtFi air interface contains blocks for preamble detection (synchronization) and cyclic redundancy check (CRC-16). The preamble is inserted after modulation and is used to mark the start of the LtFi frame. The receiver detects preamble using cross-correlation technique. The error detection using CRC is required in order to provide reliable communication over the noisy channel.

C. Modulation

This section describes the basics of LtFi’s modulation techniques. As already stated in Section II, LTE-U has to preempt (puncture) its transmission after at most 20 ms, but additional interruptions are allowed. We will use such basic 20 ms chunk of LTE-U transmission to encode just one LtFi symbol by introducing an additional puncture on a selected position in the chunk. Note, that the interruption in transmission (puncturing) do not contribute to the *on-time* of LTE-U, and the remaining data have to be transmitted in additional chunks.

For the sake of clarity of presentation, we here describe the simplest modulation process assuming that the LTE-U BS has buffered enough data and we use only a single puncture for encoding CTC data.

Without loss of generality, in Fig. 4, we present a single LtFi symbol with 20 ms duration that consists of 18 ms of LTE-U’s transmission and one puncture of 2 ms. With those values, there are ten different possible puncturing positions, but as the receiver has to correctly discover the start and the end

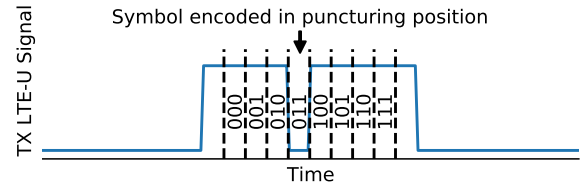


Fig. 4. Illustrative example showing modulation at LTE-U side. Here a CTC symbol encodes three bits.

of LtFi symbol, it is not possible to puncture at the first and the last position. Hence, there are only 8 possible positions, what allows for encoding of three bits in one LtFi symbol.

D. Synchronization & Demodulation

The input to our LtFi receiver is a signal created based on the observation of the relative amount of time the WiFi-NIC MAC spent in specific states, namely, *i*) idle, *ii*) receive (RX), *iii*) transmit (TX) and *iv*) interference (*Intf*) — see Fig. 5. The pseudo-code of the algorithm used for synchronization and demodulation is shown in Listing 2. Fig. 6 shows an example of received *Intf* signal in clean channel. Unfortunately, in practice, the *Intf* signal is noisy and needs to be cleaned for which we need the other three states as well (line 11-12). The preamble detector is based on calculating the cross-correlation (line 16). After a preamble is detected the receiver is synchronized and starts decoding the symbols. Therefore it computes the cross correlation to each valid symbol and takes the one with the highest value. Each symbol is afterwards de-mapped to bits (Fig. 6). The receiver continues until it decodes all symbols of the fixed length LtFi frame. Note, that the LTE-U cycle length has to be known *a priori* or discovered automatically as proposed in [8].

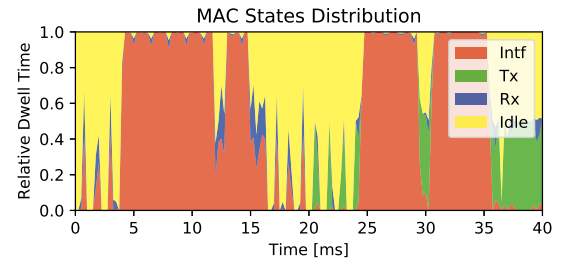


Fig. 5. Illustrative example showing the WiFi MAC states distribution.

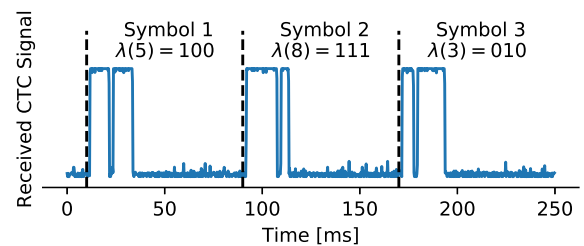


Fig. 6. Example of received signal and the demodulation at WiFi side.

E. Load-Aware Adaptive Coding Scheme

So far we assumed that there is enough LTE-U data to be transmitted so that one LtFi symbol of 20 ms duration can be

Algorithm 1: LtFi air-interface receiver (preamble detection and demodulation)

```

Input:  $T_c$  ▷ LTE-U cycle duration
Input:  $\Delta t = 250 \mu s$  ▷ Sampling interval  $\rightarrow f_s = 4 kHz$ 
Input:  $ED_t, RX_t, TX_t, IDLE_t$  The amount of time spent in each MAC state during last  $\Delta t$ 
Input:  $\tau_1, \tau_2, \tau_3 \in (0, 1)$  ▷ Thresholds for signal cleaning
Input:  $\tau_p$  ▷ Preamble Detection Threshold
Input:  $P = \{p_1, \dots, p_N\}$  ▷ Preamble Reference Signal
Input:  $M^1, \dots, M^k$  ▷ Set of  $k$  possible LtFi symbols
Input:  $L$  ▷ LtFi frame length
1  $W \leftarrow \frac{T_c}{M}$  ▷ Window Size (i.e. samples in LTE-U cycle)
2  $N \leftarrow 4W$  ▷ Preamble Length
3  $t_0 \leftarrow 0$  ▷ LtFi Symbol Start Marker
4  $s \leftarrow 0$  ▷ Synchronization Flag
5  $R \leftarrow 0$  ▷ Cross-correlation of last synchronization
6  $l \leftarrow 0$  ▷ Number of decoded symbols
7  $F \leftarrow \{\}$  ▷ Decoded bits of frame
8 while True do
9    $t \leftarrow t + 1$  ▷ For each new sample
10   $Intf_t \leftarrow ED_t - RX_t$ 
11   $S_t \leftarrow Intf_t$  ▷ Interference signal (i.e. LTE-U)
12   $S_t[S_t > \tau_1] = 1; S_t[1 - S_t > \tau_2] = 0$  ▷ Signal cleaning
13   $S_t[RX_t > \tau_3] = 0; S_t[TX_t > \tau_3] = 0; S_t[IDLE_t > \tau_3] = 0$ 
14   $S_t = S_t - 0.5$  ▷ Remove DC for better CC properties
15   $\tilde{P} \leftarrow S_{t-N}, \dots, S_t$  ▷ Last N samples of recv. signal
16   $r = \langle P, \tilde{P} \rangle = \sum_{i=1}^N m_i \times \tilde{p}_i$  ▷ Preamble Detector
17  if  $r \geq \tau_p$  and  $s = 0$  then
18     $s \leftarrow 1; R \leftarrow r; t_0 \leftarrow t$  ▷ Preamble detected  $\rightarrow$  synchronization
19  if  $r \geq R$  and  $s = 1$  then
20     $R \leftarrow r; t_0 \leftarrow t; l \leftarrow 0; F \leftarrow \{\}$  ▷ Re-synchronization with higher CC
21  if  $s = 1$  and  $t - t_0 = W$  then
22     $l \leftarrow l + 1; t_0 \leftarrow t$ 
23     $\tilde{M} \leftarrow S_{t-W}, \dots, S_t$  ▷ Received LtFi symbol
24     $\langle \tilde{M}, M^k \rangle = \sum_{i=1}^W m_i \times \tilde{m}_i^k$  ▷ Cross-correlation (CC)
     $k^* = \underset{k}{\operatorname{argmax}}(\langle \tilde{M}, M^k \rangle)$  ▷ Symbol with highest CC
25     $B = \operatorname{map}(M^{k^*})$  ▷ Symbol-to-bit mapping
26     $F \leftarrow \{F, B\}$  ▷ Append bits to frame
27    if  $l = L$  then
28      yield  $F$ 
29     $l \leftarrow 0; s \leftarrow 0; F \leftarrow \{\}$ 

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sent during a LTE-U cycle. In practice, however, as network traffic is bursty (e.g. adaptive video streaming) the duration of the LTE-U's *on-time* can be expected to be variable.

In order to deal with the issue of variable duty cycles, in LtFi we have introduced Load-Aware Adaptive Coding Scheme that selects the proper symbol length and number of punctures depending on the network load in the LTE-U network. In Table I, we show the LtFi symbol lengths together with the number of available puncture positions as well as the number of bits that can be encoded using single puncturing of 1 ms. Note, that without affecting its throughput, a LTE-U BS may use cycle and *on-time* of longer duration (i.e. the same duty-cycle) to create a LtFi symbol encoding more bits.

TABLE I
AVAILABLE LtFi SYMBOL LENGTHS

Min LTE-U <i>on-time</i>	Max LTE-U <i>on-time</i>	Available puncture positions	Number of encoded bits
4	5	2	1
6	9	4	2
10	17	8	3
18	20	16	4

F. LtFi-X2-Interface

The LtFi-X2a-Interface is an over-the-backhaul control channel between a Management Unit of the WiFi node (mostly AP) and a LTE-U network represented by the LtFiMU, while the LtFi-X2b-Interface is a control channel between the LtFiMU and each BS in the LTE-U network. Here, we use similar nomenclature as in LTE system, where X2-Interface is over-the-backhaul control channel between BSs. The setup of LtFi-X2a-Interface is always initiated by a WiFi node (AP), after successful decoding of the information transmitted over the LtFi air-interface. Specifically, it is the public IP address of the LtFiMU and ID of the transmitting LTE-U BS. The cross-technology channel enables collaboration between co-located APs and BSs and can be used by various interference and radio resource management applications — Sec. VIII. Note, that the X2 channel can be encrypted using standard protocols like TLS.

IV. MULTI-CELL OPERATION

So far we discussed the scenario where a WiFi node is co-located with just a single LTE-U BS. However, in a real environment, we can expect to have multiple co-located LTE-U BSs. In this section, we will extend the basic concepts behind LtFi in order to support a multi-cell scenario.

For the following, we assume the worst case scenario where all co-located LTE-U BSs are using the same unlicensed spectrum channel. Let us note that during channel selection procedure, each LTE-U BS tries to avoid channels already occupied by the other operators and chooses the channel occupied by its own operator. Therefore, with the high probability, all LTE-U BS operating on the same channel are managed by the single operator. Nevertheless the question of the impact of overlapping transmissions from multiple LTE-U BSs (allowed by the LTE standard supporting operation with frequency reuse one) is still opened.

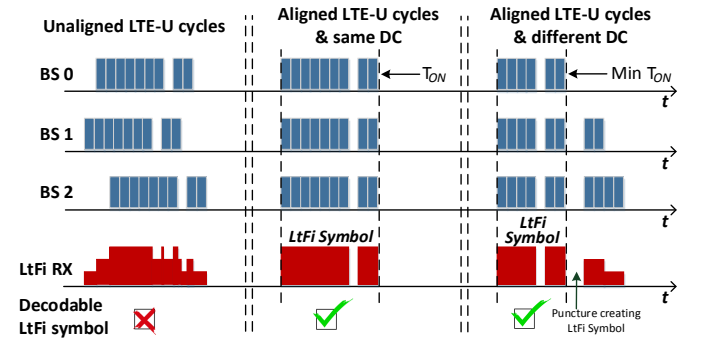


Fig. 7. Operation of LtFi in multi-cell environment.

If we simply allow each LTE-U BS to broadcast asynchronously different CTC signals imposed within the LTE-U payload as described in Section III, it would lead to very unfavorable transmission conditions. Strictly speaking, for each specific instance of CTC channel, all the other transmission should be considered as an interference making the decoding of our puncturing difficult or even impossible (i.e. the

usual SINR computations pertain properly) – Fig. 7(left). The success of our CTC transmission would be heavily dependent on the geometry, i.e. the location of WiFi station in relation to all neighbor LTE BSs. Consider the following illustrative example network given in Fig. 8 where a WiFi node A is surrounded by three LTE-U BSs. The SINR is very low and hence the decoding would fail.

The most robust solution assuring best possible CTC transmission can be achieved by two conditions imposed on a set of LTE BSs creating a neighborhood:

- i) enforcing all LTE-U BSs within this neighborhood to have aligned in phase duty-cycles,
- ii) assuring that all the of them will have embedded the same information on the CTC – Fig. 7(middle).

Note, that LTE-U BSs are not required to have the same network load as LtFi symbol is always formed using the transmission of a BS with the lowest duty-cycle – Fig. 7(right). Such coordinated transmission of the CTC information is simple to achieve if there will be a common entity controlling the duty cycles and all the LTE-U BSs in the neighbourhood (e.g. single building) are managed by a single operator.

Having constraint to transmit the same data on CTC from all LTE-U BSs, we divide the problem of proximity detection into two sub-problems: *i*) detection of the LTE-U network identified by the public IP address of its LtFiMU and *ii*) detection of the LTE-U BS IDs in interference range. The first is solved by programming all LTE-U BS to transmit the same data over CTC, i.e. public IP address. In absence of any interference, this data can be easily decoded by any WiFi node. The second is solved by introducing BS clustering in the LTE-U network where adjacent BSs are grouped in clusters of e.g. size 3. We demand that members of the same cluster have to send the same data over the CTC whereas different data can be sent by different clusters. For WiFi nodes located inside those clusters, the SINR is improved due to the absence of intra-cluster interference. This enables the WiFi node A from Fig. 8 to decode the data on the CTC channel from the cluster containing cells 0, 1 and 4. However, such a static non-overlapping clustering is not sufficient as WiFi nodes located at cluster edges will suffer from the inter-cluster interference. We solve this issue by using a dynamic (overlapping) clustering where the members of a given cluster are not fixed but change periodically. For a cluster size of three, we have six overlapping cluster configurations with changing members to cover all the six cell-edges. As with overlapping clusters, a BS is no longer a member of exactly one cluster, the overlapping clusters need to be orthogonalized in time.

We define the LtFi frame consisting of two parts, that has to be sent by each BSs synchronously — Fig 9. The first part contains the network ID, while the second part consists of the six cluster IDs that the BS is part of. Depending on the location of the WiFi node only a subset of the six cluster IDs can be decoded from which the WiFi is able to derive the set of interfering BSs. Each element of the message is protected by separate CRC. This is required in order to make sure that each part of the CTC message can be decoded independently as the

Algorithm 2: Deriving the LTE-U BSs in proximity.

Input: $C = \{(i_1, c_1), \dots, (i_n, c_m)\}$ \triangleright Set of decoded configuration number and cluster IDs
Input: Z \triangleright Code-book received from LTE-U network
1 $X \leftarrow \{Z(i, c), (i, c) \in C\}$ \triangleright Translate C into set of sets of cells IDs using code-book Z
2 $Y \leftarrow \bigcup_{A \in X} A$ $\triangleright Y$ contains cell IDs being member of any element in X
3 **return** Y \triangleright Return the set of cell IDs in proximity

receiver experiences different SINR for each of them. Note, that the start and the end of each element of the message has to be aligned with LtFi symbol boundaries. The message has a size of 30 Bytes plus four LtFi symbols for the preamble and it is repeated in an infinite loop. Note, that message is created only once for each BS after execution of clustering.

Fig. 8 illustrates LtFi’s dynamic clustering for three different WiFi node locations. At location *A* the WiFi node is able to decode the network ID and only the cluster ID 5. No other cluster IDs can be decoded. Hence, the WiFi node assumes to be located between the cells being members of cluster 5 during configuration (time-slot) 1, namely cell 0, 1 and 4. At location *B* the WiFi node is at the edge between cells 4 and 6. Here the cluster ID 4 can be decoded in configuration 2 and 3 which corresponds to the clusters {3, 4, 6} and {4, 5, 6}. Note, that in this illustrative example, we assume that the signals received from non-adjacent BSs are weak and hence have only minor impact.

Estimating LTE-U BSs in proximity: A WiFi node continuously decodes the information it receives on the LtFi air-interface. After decoding the network ID it uses the LtFi-X2a-Interface to create a control channel over the wired Internet to the corresponding LtFiMU. In the next step, the WiFi node retrieves from the LtFiMU a code-book which is required to derive the actual LTE-U BS IDs from the correctly decoded `<configuration/slot number, cluster ID>` tuples. Note, this is required as we apply dynamic (overlapping) clustering in the LTE-U network. We represent the code-book as a matrix which is constructed as follows. The entry in row *i* and column *j* contains the set of cell IDs being member of the cluster *i* in configuration (time-slot) *j*. Note, for a cluster size of three we need six overlapping cluster configuration, hence $i, j \in (1, 6)$. The matrix shown below is the code-book for the example given in Fig. 8. Here only the entries for the clusters with ID 4 and 5 are shown:

$$Z = \begin{bmatrix} \vdots & & & & & & \\ \{3, 6\} & \{3, 4, 6\} & \{4, 5, 6\} & \{5, 6, \} & \{2, 4, 5\} & \{2, 5, \} \\ \{0, 1, 4\} & \{0, 1, \} & \{1, 2, \} & \{1, 2, 4\} & \{1, \} & \{6, \} \\ \vdots & & & & & & \end{bmatrix}$$

The final step is the computation of the set of BS IDs from the data received over the LtFi air interface for which the algorithm is shown in Listing 2. For our example from Fig. 8 the WiFi node at location B would have $C = \{(2, 4), (3, 4)\}$ and

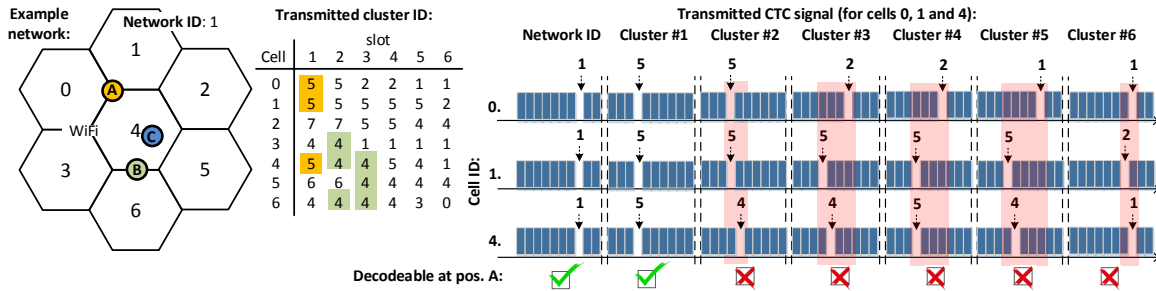


Fig. 8. Example network consisting of multiple co-located LTE-U BSs and WiFi node placed at the three different locations (A,B,C). For illustration, each CTC symbol encodes 3 bits of information. Table shows for each cell (BS) ID the cluster IDs for the six configurations.

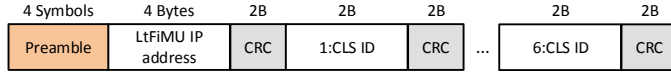


Fig. 9. Structure of LtFi Air-Interface frame.

with code-book Z it would calculate:

$$X = \{\{3, 4, 6\}, \{4, 5, 6\}\}$$

$$Y = \{3, 4, 5, 6\}$$

Hence, the LTE-U BSs in the proximity of WiFi node at location B are 3, 4, 5 and 6.

V. TRANSMISSION RATE ANALYSIS

Here we provide a theoretical analysis of the achievable data rate on the LtFi air-interface. As mentioned in Sec. III-A, there is one mandatory puncture of 2 ms duration that has to be applied to LTE-U's transmission every 20 ms. In LtFi we keep this mandatory puncturing so that those 20 ms chunks represent the LtFi symbols of the maximal duration. Note, that z LtFi symbols can be present during single LTE-U cycle with duration of T_{cycle} . Inside the symbol, we can add up to k additional punctures of 1-2 ms duration to encode CTC data bits. By increasing k more bits can be encoded into a single LtFi symbol. The number of available symbols M can be computed as the binomial coefficient (1), where n is the number of possible puncturing positions. The transmission rate can be computed using equation (2):

$$M = \binom{n}{k} = \frac{n!}{k!(n-k)!}, \quad 0 \leq k \leq n \quad (1)$$

$$R[bps] = \frac{\lceil \log_2(M) \rceil \cdot z}{T_{cycle}} \quad (2)$$

Note, that when increasing k the LTE-U BS has to send its remaining data in additional chunks, that can be used to create additional LtFi symbols (i.e. z grows).

Fig. 10(left) shows the data rate of the LtFi air-interface with increasing number of punctures ($k \in \{0, 1, \dots, 9\}$) of 1 ms duration for different values of LTE-U *on-time* and period of 90 ms. Here, we use only the LtFi symbols of 20 ms duration. We can observe that for large k and *on-time* of 44 ms a data rate of up to 665 bps can be achieved. For a shorter *on-time* of 20 ms the data rate is between 44 and 166 bps depending on the number of punctures per symbol k . The transitions between

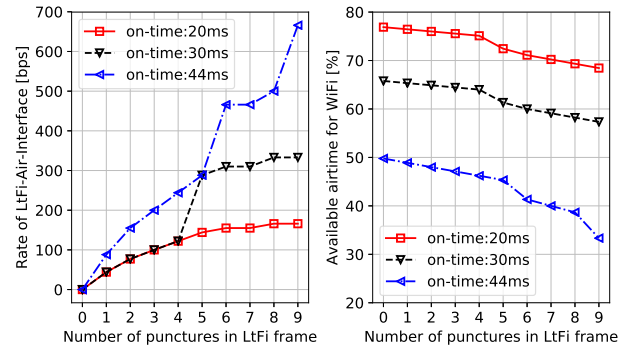


Fig. 10. Analytical results of the LtFi air-interface.

the different number of LtFi symbols within the LTE-U cycle (z), caused by the different number of additional punctures, can be easily noticed.

We have also performed the analysis of the impact of LtFi on WiFi and its effective available air-time – Fig. 10(right). Since WiFi uses random channel access it may happen that it starts its transmission just before the start of the *on-time* or within a puncturing, leading to cross-technology interference and possible packet loss. For our analysis we took the worst-case scenario, i.e. each WiFi packet transmission being overlapping with an ongoing LTE-U transmission is assumed to be lost. As WiFi frame duration we assumed $384 \mu s$ ¹. Thus, in the worst case only roughly 0.6 ms out of 1 ms puncture is available for WiFi transmission. Such a collision can also lead to packet loss in the LTE-U network. Especially the first slot (0.5 ms) after a puncturing is prone to collisions for which we suggest to use either a more robust MCS or power bursting.

Takeaways: The data rate of the LtFi air-interface is sufficient to deliver connection and identification information to co-located WiFi nodes, i.e. it takes at most 10 s with the lowest and less than 1 s with the highest data rate. We argue that it is enough to support not only static but also nomadic environments (e.g. smartphone in WiFi tethering).

VI. EXPERIMENTAL EVALUATION

This section presents an overview of the LtFi prototype implementation and measurement-based performance evaluation of its air-interface.

¹According to [3] 97% of the WiFi frames have a duration of less than $384 \mu s$.

A. LtFi transmitter – LTE-U BS

The LtFi transmitter was implemented using srsLTE [9], which is an open-source software-based LTE stack. It runs on a host machine and generates a waveform that is sent to Ettus USRP (X300 in our case) for over-the-air transmission. As LTE-U is not supported in public srsLTE repository, we applied several modifications to eNB code. Specifically, we have implemented LTE-U's duty-cycled channel access scheme, where we can program the duration of *on* and *off-time* of single LTE-U cycle as well as inject multiple punctures during the *on-time*. In addition, we provide a Python-based application that hides the complexity of the transmitter (including data modulation and preamble/CRC generation) behind a simple API allowing for sending messages. The application translates the message into the chain of LtFi symbols and passes it to the eNB scheduler. Moreover, we have exposed a function for controlling the RF gain of the USRP, that allows us to set different transmission power level of LTE-U BS.

B. LtFi receiver – WiFi node

For the WiFi node, we have selected off-the-shelf equipment using Atheros AR95xx chipset as it allows direct monitoring of the signal detection logic of the WiFi NIC at a very fine granularity level. More details on Atheros signal detection logic can be found in [8] and the patent from Atheros [10]. We sample the Atheros registers with a rate of 4kHz and process the data in blocks of 1s window sizes. For this purpose, we migrated the RegMon tool [11] to SMP systems (Ubuntu 16.04) and provided a patch to the upstream ath9k wireless driver. Moreover, we replaced the ring buffer in Regmon by relay file system (relayfs) as it provides an efficient mechanism for transferring large amounts of data from kernel to userspace. The LtFi receiver was implemented entirely in Python language. It runs in real-time occupying only up to 15% of a single core of i5-4250U (1.30 GHz) CPU time.

C. The experiment setup

The experiment setup consists of a single LTE-U BS and two WiFi BSSs (AP with associated STA). LtFi was running on one of the WiFi APs which was placed 2m away from the LTE-U BS. The second BSS was used for background traffic generation. During the experiment the transmission power of the LTE-U BS (hence LtFi TX) was varied. The LTE-U CSAT period and *on-time* duration was set to 40 ms and 19 ms, respectively. With such configuration and using single puncture with duration of 1 ms, LtFi achieves a transmission rate of 100 bps. As we use single BS, we transmitted only the first part of LtFi frame consisting of 4 preamble symbols, 4 bytes of IP address and 2 bytes of CRC sum – 20 LtFi symbols in total.

As performance metric for the LtFi air-interface, we selected the LtFi Frame Error Rate (FER) and LtFi Symbol Error Rate (SER). We measured both values for different received signal strength levels of the LTE-U signal at the LtFi-enabled WiFi node in four different scenarios, namely:

- 1) **Clear Channel:** the wireless channel was free from WiFi traffic and only the LTE-U BS was transmitting during its *on-time*. The four WiFi nodes were idle.
- 2) **Background Traffic:** similar to 1.), except that the non-LtFi WiFi BSS was generating WiFi background traffic. We distinguished between two cases, namely i) light (UDP 10Mbit/s) and ii) heavy (backlogged TCP) traffic.
- 3) **WiFi AP DL:** similar to 1.), except that the LtFi-enabled AP itself was generating traffic to its client station. As in scenario 2, we have two cases with light and high load.

The *Clear Channel* scenario represents the simplest environment for LtFi due to the absence of any other signal except the LTE-U. The *Background Traffic* is more challenging as the LtFi RX node receives a mix containing both LTE-U and WiFi signals. The last scenario, *WiFi AP DL* is the worst case as here the LtFi-enabled AP is additionally transmitting itself WiFi traffic and thus — due to the half-duplex constraint — is temporarily unable to receive the LtFi signal.

D. Measurement Results

Fig. 11a shows the FER for the three different scenarios. We can clearly see that the LtFi air-interface is able to operate close to the receive signal strength required for energy detection based carrier sensing. For example in *Clear Channel* scenario a power level of -60.5 dBm is sufficient to reliably decode LtFi frames. For the other two scenarios a slightly higher receive power is required, i.e. up to -57 dBm for *Background Traffic (high)*. Moreover, we see a very narrow region with intermediate FERs, i.e. 1-2 dB for *Clear Channel*. Finally, we see that in *WiFi AP DL (high)* the FER stays above 20% even for high receive power levels. This can be explained by the mentioned half-duplex constraint. The SER is shown in Fig. 11b. Interestingly, here the SER is smallest in *Background Traffic (light)*. The RX signal caused by the light WiFi traffic helps to clean *Intf* signal (see Listing 2, lines 11-12).

So far we kept the Energy Detection (ED) threshold of the LtFi RX node constant at its default configuration (i.e. -62 dBm). Fig. 11c shows the FER for the *Clear Channel* scenario for different ED values². Note, the black curve corresponds to the default configuration used in the Atheros WiFi NIC ($\theta = 28$). The highest sensitivity was achieved with $\theta = 3$, where LtFi is able to decode the signal at very low receive power levels, i.e. -92 dBm.

Takeaways: The information sent over the LtFi air-interface can be reliably decoded even at very low LTE-U receive power levels.

VII. SYSTEM-LEVEL SIMULATIONS

In addition to the measurements reported above, we have used simulation for the sake of LtFi performance evaluation in larger system setting. The objective was to show that a WiFi node is, indeed, able to estimate the set of LTE-U BSs in its proximity.

²Atheros chips allows for changing ED threshold by writing its value to AR_PHY_CCA register.

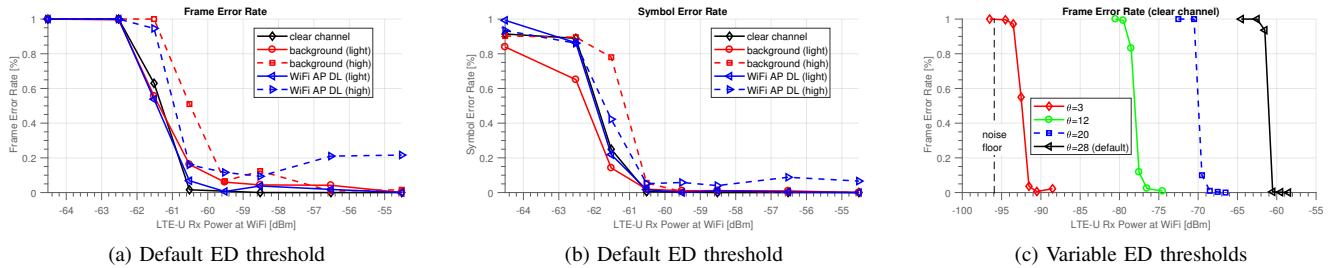


Fig. 11. LtFi demodulator performance — Frame Error Rate (FER) / Symbol Error Rate (SER) vs. LTE-U RX power

TABLE II
SIMULATION PARAMETERS.

Parameter	Value
LTE-U BS Number	100
LTE-U Antenna type	omni-directional
LTE-U TX power/FFR/MAC	20 dBm/1/CSAT
LtFi RX sensitivity rel. to noise	19 dB (-77 dBm)
Pathloss model	Motley-Keenan ($\alpha = 0.44$)
Correlated shadowing σ	0 & 6 dB

A. The model

We conducted system-level simulations using Matlab according to the methodology recommended by the IEEE 802.16m group [12]. The setup mimics an indoor small office scenario. The LTE-U BSs are placed in a hexagonal grid with inter-BS distance set to 50 m. All of them are using the same unlicensed channel (5.2 GHz) and are transmitting the LtFi signal as described in Sec. IV. The LtFi receiver was placed on a regular grid in the bounding box with the side length of 140 m. The remaining parameters are summarized in Table II.

For the simulations, we used the following simplified model according to which the LtFi receiver is able to perfectly decode the message as long as the observed CTC signal was above and the sum of interfering CTC signals was below the sensitivity level. The value of sensitivity level was selected to be -77 dBm (i.e. 19 dB above the noise floor), as it achieves the best performance in the defined scenario³. Note, that modern WiFi NICs allow for tuning of ED threshold, what can be used to develop an adaptation mechanism aiming to improve SER of LtFi receiver. At each location, the LtFi proximity detection algorithm (Listing 2) was executed in order to estimate the number of LTE-U BSs in its vicinity.

B. Simulation Results

Fig. 12a shows the estimated number of neighboring LTE-U BSs for each LtFi receiver location. In absence of shadowing, i.e. $\sigma = 0$, we can observe a strong correlation between the LtFi's receiver positions and the number of estimated LTE-U BSs. When the LtFi receiver is placed close a single LTE-U BS the number of reported BSs is up to seven whereas for locations between three BSs the reported number is three. Finally, Fig. 12b shows the results for an environment with Shadowing, i.e. $\sigma = 6$.

Takeaways: A LtFi-enabled WiFi node is able to accurately identify the interfering LTE-U BSs in its proximity.

³In case of Atheros WiFi NIC the ED is configured with $\theta = 23$.

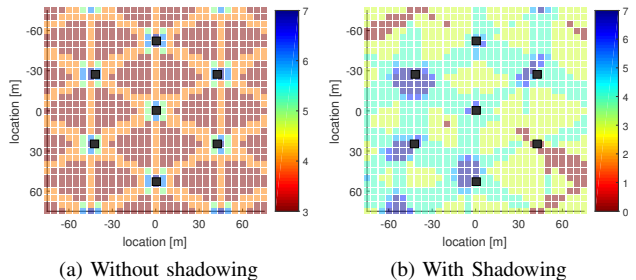


Fig. 12. Number of detected LTE-U BSs at each spatial location. Black rectangles mark the location of LTE-U BSs. An ED threshold of $\theta = 23$ (-77 dBm) is used.

VIII. LtFi APPLICATIONS

A. Cross-technology Contention & Interference Management

Co-located LTE-U and WiFi networks suffer from performance degradation due to either contention or co-channel interference. Both problems are already partially addressed by usage of the CSAT by the LTE-U BSs. However, the period and duty cycle are updated on a rather long-term basis and only based on the LTE-U base station perspective of the spectrum. Thus, in case of a cross-technology hidden terminal problem, the BS fails to calculate fair CSAT parameters. We believe that collaboration channel enabled by LtFi can be used to optimize co-existence and enable cooperation between interfering networks allowing them to negotiate a fair usage of the shared radio resources.

The collaboration channel opens a way towards cross-technology distributed self-organizing networks (SON) idea. Now the co-located networks can evaluate different configurations of wireless parameters as they have a possibility to obtain feedback about its impact on their direct neighbors' performance. In this way, for example, LTE-U eNB may try out different beam-forming configurations, and find one that causes nulling in the direction of WiFi AP [13]. In a similar way, WiFi nodes can test different thresholds values of energy-based carrier sensing, transmission power, etc.

Finally, many solutions already envisioned in the literature [14], [15], [16], [17], [18] would directly benefit from our LtFi system. For example, Duet [19] assumes that LTE-U BSs are equipped with an additional WiFi interface used to count a number of active WiFi stations based on overheard frames. With the usage of LtFi, the additional interface is superfluous, as the BS can get those data directly from neighboring APs.

B. QoS support

As LTE-U constitutes a new source of interference with a strong impact on WiFi ensuring QoS in WiFi is challenging. Especially, we can expect that the network traffic requiring low-latency (VoIP, video conferencing, etc.) will suffer the most. Using LtFi a WiFi network can communicate its resource requirements necessary to support the desired QoS to the co-located LTE-U network. For example, in case of low-latency traffic in WiFi network, it can ask LTE-U BS over LtFi-X2-Interface to add additional punctures in its *on-time*.

IX. RELATED WORK

So far, the research focus was to enable cross-technology communication between WiFi and sensor networks (mostly ZigBee), that coexist in the same 2.4GHz band. Esense [20] and HoWiES [21] enable over-the-air WiFi to ZigBee communication by injecting dummy packets with durations that are unlikely to be used in normal WiFi traffic. They can achieve relatively high throughput but are a burden to already saturated spectrum. GapSense [22] prepends legacy packets with a customized preamble containing sequences of energy pulses. The length of silent gaps between them encodes the CTC data to be transmitted. Such approach requires a dedicated hardware and is not compatible with COTS devices. FreeBee [5] modulates CTC data by shifting the timing of periodic beacon frames but suffers from low data rate being limited by the beacon rate. C-Morse [3], DCTC [23], EMF [4] and WiZig [24] achieve high CTC rates by utilizing all types of frames. In general, they are compliant with existing standards and strive to be transparent to upper protocol layers. They slightly perturb the transmission timing of WiFi frames to construct recognizable radio patterns within negligible delay. In contrast, in case of LTE-U, we cannot modify the transmission timing, as it is tightly scheduled.

The basic philosophy for establishing an over-the-backhaul control channel between pairs of base stations managed by different operators has been introduced in [25] and [26] for the case of homogeneous WiFi systems. LtFi extends this idea towards cross-technology control between heterogeneous networks.

X. CONCLUSIONS

This paper introduces LtFi, the first system that enables the cross-technology communication between LTE-U and WiFi. In contrast to other related studies in CTC, that focus only on enabling the direct communication between heterogeneous wireless technologies, LtFi is a holistic solution allowing for over-the-air cross-technology neighbor discovery and identification as well as the establishment of wired (over the Internet) control channel between co-located and interfering LTE-U and WiFi networks. Such a control channel can be used for coordination and enables performing cross-technology interference and radio resource management.

LtFi is fully compliant and transparent with LTE-U technology and works with WiFi COTS hardware, what was

confirmed with our prototypical implementation using open-source LTE stack and Atheros NIC. Our experiment results show that LtFi frames can be reliably decoded even at very low received power (i.e. -92 dBm) and provides throughput up to few hundreds of bits per second.

For future work, we plan to evaluate LtFi in real-world scenarios including non-regular placement of multiple LTE-U BSs and different types of interferers like LTE-LAA/MultiFire.

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