Future Dense Wireless Networks

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WLANs

- User-driven / Decentralized Management
- Shared spectrum
- Chaotic Deployments

Coexistence between WLANs is the next big challenge
High-density WLAN deployments

<table>
<thead>
<tr>
<th>Scenario (area, m²)</th>
<th>APs</th>
<th>STAs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stadium (~12,500 m²)</td>
<td>&gt; 1000</td>
<td>&gt; 50,000</td>
<td>Large events that require many APs to provide a satisfactory connectivity service able to support video uploading/downloading.</td>
</tr>
<tr>
<td>Train (~600 m²)</td>
<td>&lt; 10</td>
<td>&gt; 1000</td>
<td>Full coverage inside a train to provide both work and entertainment services.</td>
</tr>
<tr>
<td>Apartment building — 4 floors, 6 apartments/ floor (~2400 m²)</td>
<td>&gt; 120</td>
<td>&lt; 480</td>
<td>Several short-range APs deployed in each apartment, offering full coverage and high data rates for bandwidth hungry entertainment applications, as well as connectivity for house appliances. Community APs may also be deployed in the corridors and shared spaces.</td>
</tr>
</tbody>
</table>
Source: Ericsson Mobility Report 2015 (November)
WLAN evolution

- Improve performance
  - High-order modulations, channel coding
  - Wider channels ~ channel bonding
  - Multi-user transmissions (MIMO, OFDMA)
- Improve coexistence
  - Dynamic Transmit power & Sensitivity Adaptation
  - Dynamic spectrum selection

Next PHY/MAC amendment: IEEE 802.11ax-2019
Channel Bonding

- Increasing W (channel width), the transmission rate increases
- **Challenge**: WLANs in the same area may overlap
Static Channel Bonding

- DIFS
- Transmissions from other WLANs
- Backoff
Goals

- Characterise the interactions between overlapping WLANs in dense scenarios.
  - Traditional IEEE 802.11 analysis is not valid
  - Markovian models
  - Stochastic geometry models

- Design and evaluate different channel access strategies when using wider channels
  - Static and Dynamic Channel Bonding

- Design decentralized WLAN self-configuration protocols
  - Channel width and channel center frequency, transmission power, CCA levels
Optimal Solution

Optimal Channel Allocation:
(1-19 channels available)

CA = \{1 – 8\},
CB = \{13 – 16\},
CC = \{9 – 12\},
CD = \{1 – 8\},
CH = \{13 – 16\},
CE = \{9 – 12\},
CF = \{1 – 8\},
CG = \{13 – 16\}
CSMA/CA-SCB Markovian models

Channel Allocation
CA = \{1, 2, 3, 4\},
CB = \{4, 5\},
CC = \{5, 6, 7, 8\}
CD = \{5\}

Fig. 3. Snapshot of the temporal evolution of the system considered in the example of Section IV-F. In the vertical axis, \(Y(t)\) represents the amount of remaining backoff (white area) or transmission duration (blue area). The arrows inside the plot represent new packet arrivals.

CSMA/CA-SCB Markovian models

\[ \theta_{i,j} := \frac{\rho_{i,j} \lambda_{i,j}}{\mu_{i,j}} = \frac{\rho_{i,j} E[T_{i,j}(c_i, \gamma_{i,j}, L_{i,j})]}{E[B_{i,j}]} \]

\[ \pi_0 = \frac{1}{\sum_{s \in \Omega(C)} \prod_{u_{i,j} \in s} \theta_{i,j}} \]

\[ \pi_s = \frac{\prod_{u_{i,j} \in s} \theta_{i,j}}{\sum_{s \in \Omega(C)} \prod_{u_{i,j} \in s} \theta_{i,j}}, \quad s \in \Omega(C). \]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Computation</th>
<th>Throughput per node [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node</td>
<td>$\alpha L$ [Mbps]</td>
<td>$E[T(c, \gamma, L)]$ [msecs]</td>
</tr>
<tr>
<td>$a$</td>
<td>18</td>
<td>0.1790</td>
</tr>
<tr>
<td>$b$</td>
<td>8</td>
<td>0.2070</td>
</tr>
<tr>
<td>$c_1$</td>
<td>10</td>
<td>0.2150</td>
</tr>
<tr>
<td>$c_2$</td>
<td>22</td>
<td>0.1790</td>
</tr>
<tr>
<td>$d$</td>
<td>12</td>
<td>0.2630</td>
</tr>
</tbody>
</table>

**Example 1**

| Node | $\alpha L$ [Mbps] | $E[T(c, \gamma, L)]$ [msecs] | $p(\gamma)$ | $\rho$ | Analysis | Simulation |
| $a$ | 4 | 0.1790 | 0.10 | 0.0744 | 4.00 | 3.9 |
| $b$ | 12 | 0.2070 | 0.10 | 0.3845 | 12.00 | 12.00 |
| $c_1$ | 20 | 0.2150 | 0.15 | 1.0000 | 11.18 | 11.06 |
| $c_2$ | 5 | 0.1790 | 0.20 | 0.4752 | 5.00 | 5.00 |
| $d$ | 24 | 0.2630 | 0.05 | 1.0000 | 19.00 | 19.06 |

**Example 2**
CSMA/CA-SCB Markovian models

- Markov chain is time-reversible
  - Product-form solution
  - Insensitivity to the backoff and service time distribution
- All maximal states are dominant (given $\lambda >> \mu$)
  - We can calculate the perf. of complex networks by only finding the maximal states

Results in large groups of WLANs

- Channel position (in the spectrum): random
- Proportional fair solution (assuming complete knowledge of the network)

\[
\max_p \sum_{i=1}^{M} \log \sum_{C \in \mathcal{K}} p(C) x_i(C)
\]

s.t. \( \sum_{C \in \mathcal{K}} p(C) = 1 \)

\( p(C) \in [0,1], \text{ for all } C \in \mathcal{K}. \)

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**Algorithm 1** Waterfilling Algorithm

1: assign to each WLAN a single basic channel, i.e., \( c_i = 1 \)
   for all \( i = 1, \ldots, M. \)

2: loop

3: for \( i = 1, \ldots, M \) do

4: if \( 2c_i + \sum_{j \neq i} c_j \leq N \) then

5: \( c_i \leftarrow 2c_i \)

6: else

7: goto 11

8: end if

9: end for

10: end loop

11: For each WLAN \( i \), select the basic channels as the contiguous set
   \[ 1 + \sum_{j<i} \min(c_j, W_{\text{max}}), \sum_{j \leq i} \min(c_j, W_{\text{max}}) \] modulo \( N. \)
Results: SCB in dense networks of WLANs
Dynamic Channel Bonding

Alternatives:
- Static Channel Bonding
- Dynamic Channel Bonding
  - Selection of the wider available channel
  - Randomization between the set of available channels
The Markov chain is non-time reversible.
CSMA/CA-DCB Markovian models: Example 1

Insensitivity does not hold!
CSMA/CA-DCB Markovian models: Example 2
CSMA/CA-DCB Markovian models: Example 2

There are non-maximal states that are dominant

(a) Steady-state probabilities. The states are arranged in their order of discovery.
CSMA/CA-DCB Markovian models: Example 2

(b) Temporal evolution of the dominant states

Large switching times between groups of dominant states
DCB in large groups of WLANs

```plaintext
1 i = 0;
2 k = 0;
3 s_k = \emptyset;
4 while s_k \in \{s_0, \cdots, s_i\} do
5     s = s_k;
6     for every WLAN \ X do
7         if \ \exists n, j \ such \ that \ X^{j}_{n} \in s \ then
8             s \rightarrow s - X^{j}_{n} \ is \ a \ new \ transition;
9             if s - X^{j}_{n} \notin \{s_0, \cdots, s_i\} then
10                 i = i + 1;
11                 s_i = s - X^{j}_{n};
12         else if S_{s+x} \neq \emptyset then
13             \hat{n} = \max\{n \mid s + X^{j}_{n} \in S_{s+x}\};
14             for every \ j \ such \ that \ X^{j}_{\hat{n}} \in S_{s+x} do
15                 s \rightarrow s + X^{j}_{\hat{n}} \ is \ a \ new \ transition;
16                 if s + X^{j}_{\hat{n}} \notin \{s_0, \cdots, s_i\} then
17                     i = i + 1;
18                     s_i = s + X^{j}_{\hat{n}};
19             k = k + 1;
```
Results: DCB in dense networks of WLANs

Adaptively changing the primary channel position may further improve DCB performance.
Final remarks

- Next-generation WLANs will face many challenges related to traffic load and network density

- Coexistence is one of the biggest problems in Future Dense WNs
  - Smart & dynamic decentralized solutions

- Envisioning Future Wireless Networks
  - Hundreds of short-range & smart APs providing point-to-point like links to users using all available spectrum
Bibliography

- B. Bellalta; "IEEE 802.11ax: High-Efficiency WLANs”. IEEE Wireless Communications. February 2016.

