LTE in Unlicensed Spectrum

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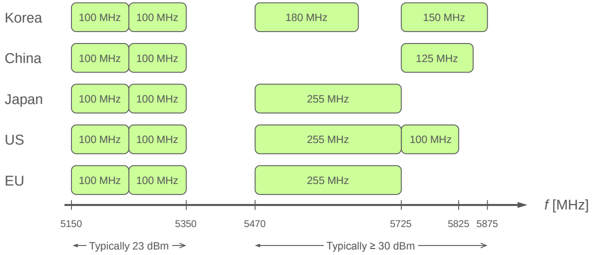
Motivation

- Demands for mobile traffic have been increasing exponentially, and will continue to increase dramatically for some years.
- The supply of (licensed) frequency spectrum allocated to cellular opeartors is very limited; operators have been feeling the crunch.
- Meanwhile, an abundance of unlicensed spectrum, 800 MHz below 6 GHz



(from C. Hoymann, "LTE in unlicensed spectrum—technical and regulatory aspects")

- A major topic of the day in the wireless industry: Can unlicensed spectrum be used effectively for cellular services? If so, how?

3GPP activities on unlicensed LTE (LTE-U)

- Dec. 2013: Qualcomm & Ericsson, "Introducing LTE in Unlicensed Spectrum"
  - LTE as supplemental downlink in 5725–5850 MHz in USA;
  - LTE enhancements for unlicensed spectrum (e.g., listen-before-talk).
- Jan. 2014: An "unofficial" workshop on LTE in unlicensed bands. Organized by Huawei, Ericsson, Qualcomm, China Mobile and Verizon. 20 companies presented.
- March 2014: 3GPP plenary meeting.
  - More operators supported to accelerate LTE-U: Verizon, China Mobile, NTT DoCoMo, T-Mobile USA, Deutsche Telekom, TeliaSonera, and China Unicom;
  - Also supported by most infrastructure and device vendors;
  - Opposition led by Orange, with Telefónica, Vodafone, AT&T, Sprint and a handful of vendors proposed to slow down.
- June 2014: next meeting.

Unlicensed LTE and its advantages

- Spectrum selection
  - < 6 GHz preferred due to path loss;
  - 2.4 GHz most crowded with existing WiFi and bluetooth;
  - Residential wireless LAN also uses the lower end of the 5 GHz band;
  - The most suitable is perhaps in the 5–6 GHz band, especially the higher end of it.
- LTE technology and eco-system are mature.
- Efficient air interface. E.g., downlink throughput of TD-LTE vs. WiFi:
  - With 1 UE, LTE slightly higher than WiFi;
  - The total throughput of LTE increases with the number of UEs;
  - The total throughput of WiFi decreases with the number of UEs.
- Unified operation and management (unlike LTE$+$WiFi).
- Guaranteed user experience.
- Need only eNB upgrade.

Digression: Licensed vs. unlicensed

- Spectrum sharing models:
  - licensed—exclusive use;
  - unlicensed—commons, need etiquette rules for sharing (e.g., 802.11);
  - hierarchical, with primary and secondary users.
- Allocated and regulated by governments.
- Licensed spectrum advocated by wireless operators (AT&T, Sprint, Verizon, ...).
- Unlicensed spectrum advocated by DARPA, Google, Microsoft, ...
- Here we put aside the licensed vs. unlicensed policy debate; we focus on the existing and future unlicensed spectrum bands.

The challenge of shared unlicensed spectrum

- Can multiple technologies share the unlicensed spectrum bands?
- How can intrinsically selfish operators/users share the spectrum?
- A fundamental challenge: tragedy of the commons.

Our work

- ... first proposes static mechanisms for selfish operators to share unlicensed spectrum bands;
- Then, in the case of time-varying traffic, dynamic sharing mechanisms are introduced.
- Related work by R. Elkin, A. Parekh, and D. Tse, "Spectrum sharing for unlicensed bands" considered backlogged traffic and static sharing mechanisms only.

A general model

- N colocated operators share bands of unlicensed spectrum $S \in (0, \infty)$.
- The random traffic intensity of operator i at time t: Λ_t^i.
- The strategy is the power spectral density $p_t^i(f)$, regulated to be below p.
- $\gamma_t^i(f) = p_t^i(f) / (\sum_{j \neq i} p_t^j(f) + \sigma^2)$.
- Utility:

$$u(p_t^i, p_t^{-i}, \lambda_t^i) = \phi\left(\int_S \rho(\gamma_t^i(f)) \mathrm{d}f, \lambda_t^i\right)$$

Assume: $\forall \lambda$, $\phi(\cdot, \lambda)$ is increasing and concave; $\rho(\cdot)$ is increasing, and

$$\rho\left(\frac{p}{\sigma^2}\right) > \sup_{n \geq 2} \; n\rho\left(\frac{p}{(n-1)p + \sigma^2}\right).$$

- Expected utility:

$$U^i(p_t^i, p_t^{-i}) = \mathsf{E}\left\{u(p_t^i, p_t^{-i}, \Lambda_t^i)\right\}$$

- Total value at the present time:

$$V^i = (1-\delta) \sum_{t=1}^{\infty} \delta^{t-1} U^i(p_t^i, p_t^{-i})$$

A two-operator on-shot game

- Assume saturated traffic and

$$u(p_t, q_t) = \int_S \log_2 \left(1 + \frac{p_t(f)}{\sigma^2 + q_t(f)}\right) \mathrm{d}f$$

- If noncooperative, both use full spectrum with maximum power:

$$R = W \log_2 \left(1 + \frac{p}{p + \sigma^2}\right) \approx W$$

- If fully cooperative, each use a different half with maximum psd:

$$C = \frac{W}{2} \log_2 \left(1 + \frac{p}{\sigma^2}\right) = \frac{W}{2} a$$

Operator 2

Operator 1	Spectral Efficiency	N	Y
	N	0, 0	0,8
	Y	8,0	1,1

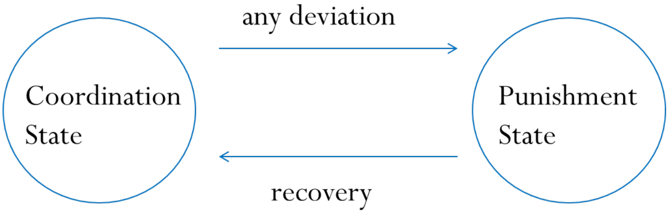
Non-cooperative: $R = W$

Equilibrium

Cooperative: $C = 4W$

Multiple time slots (repeated game)

- Can selfish operators willingly and honestly cooperate?
- Yes, in case of multiple time slots, if presented with an equilibrium.



Static sharing

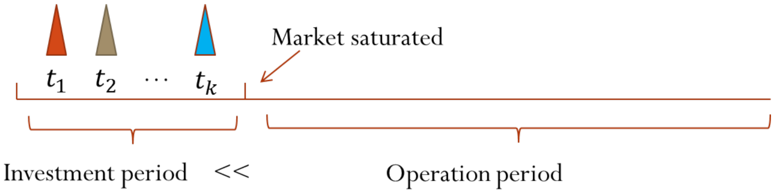
- Let $\{p_o^i\}_{i=1}^N$ be the strategy profile of any cooperative sharing scheme.
- Each operator observes the spectrum activities of all other operators.
- Mechanism of operator i:
  - I Play p_o^i so long as operator j plays p_o^j for every $j \neq i$;
  - II Play full spectrum strategy for T periods if some operator deviates and then return to I;
  - III If any other operator deviates in phase II, then repeat phase II.

Theorem

If δ is large enough, the proposed mechanism is a Nash equilibrium for N operators. Moreover, it is a subgame perfect Nash equilibrium.

Entry game

- Tragedy of commons?
- No, if the investment cost is high enough.
- A new operator may
  - enter if investment cost is lower than the value to be gained;
  - stay out if investment cost is higher.
- An incumbent operator may
  - deter a new operator by fully interfering with it;
  - cooperate if the total interference is not enough to deter entry.



How many operators may enter?

- U_f denotes the utility achieved by using the full spectrum.
- N^* satisfies $U_f(N^* + 1) \leq C$ and $U_f(N^*) > C$.
- Strategy of the i-th operator to arrive:
  - If $i > N^*$, then stay out.
  - If $i \leq N^*$, then make the investment and play the game.
- Strategy of an incumbent operator:
  - If there are no more than N^* operators, cooperate; when a deviation by any other operator is detected, use the full spectrum thereafter.
  - If there are more than N^*, always use the full spectrum.

Theorem

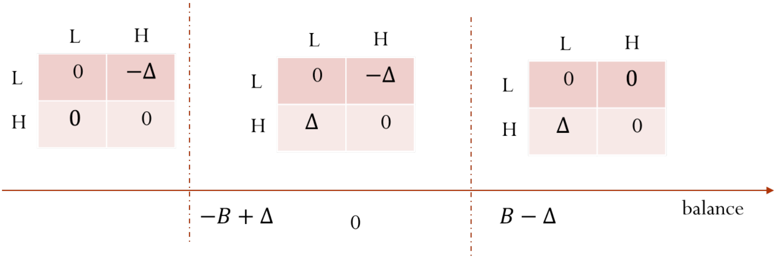
The preceding strategy is a subgame perfect Nash equilibrium for the entry game, which guarantees the first N^* operators to enter are profitable.

Dynamic sharing with time-varying traffic

- Recall
$$u(p_t^i, p_t^{-i}, \lambda_t^i) = \phi\left(\int_S \rho(\gamma_t^i(f))\mathrm{d}f, \lambda_t^i\right)$$
- We focus on orthogonal sharing, so
$$u(w, \lambda) = \phi\left(w\rho\left(\frac{p}{\sigma^2}\right), \lambda\right)$$
$$\frac{\partial u(w,\lambda)}{\partial w} > 0, \ \frac{\partial^2 u(w,\lambda)}{\partial w^2} < 0$$
- Assume supermodularity: Additional spectrum yields larger utility improvement in the case of heavier traffic, i.e., if $\mu > \lambda$,
$$u(w+\Delta,\lambda) - u(w,\lambda) < u(w+\Delta,\mu) - u(w,\mu).$$
- Spectrum trade with direct payment. Accounting and billing are difficult; may also encourage spectrum trolls.
- We focus on trading without direct payment.

Cooperation

- Yield some spectrum in case of light traffic and that another operator wishes to borrow; borrow some spectrum in case of heavy traffic and that another operator can yield.
- Balance constraint: $|b_t^i| \leq B, \ \forall \ t$ and i. The cap prevents infinite deficit.
- Illustration for the case with 2 operators and 2 traffic levels:



Example: 2 operators and 2 traffic levels

- The two operators are symmetric.
- Strategy of operator 1:
  - I In the normal state:
    reveal the traffic level λ_t^1 to and collect λ_t^2 from operator 2;
    borrow Δ if $\lambda_t^1 > \lambda_t^2$;
    lend Δ if $\lambda_t^1 < \lambda_t^2$.
    If operator 2 deviates, enter the punishment state.
  - II In the punishment state, use full spectrum and maximum power for T periods, then return to the normal state.
  - III If operator 2 deviates in phase II, then repeat phase II.

Theorem

If $\mathsf{P}(\Lambda_t^1 > \Lambda_t^2) > 0$, $\mathsf{P}(\Lambda_t^1 < \Lambda_t^2) > 0$, *and* δ *is large enough, then* $\exists\ \Delta > 0$, *s.t. the preceding strategy with truth-telling is a subgame perfect Nash equilibrium.*

An example and comparison

- Traffic $\Lambda \in \{0, 1\}$.
- Instantaneous utility: $\psi(\lambda) R$, where R is the data rate.
- Fully interference: $u_f(\lambda) \approx \psi(\lambda) W \log_2(1+1)$
- Static sharing: $u_s(\lambda) = \psi(\lambda) \frac{W}{2} \log_2\left(1 + \frac{p}{\sigma^2}\right)$.
- Dynamic sharing: $u_d(\lambda_1, \lambda_2) = \psi(\lambda_1) R(\lambda_1, \lambda_2)$.
- Assume $\log_2\left(1 + \frac{p}{\sigma^2}\right) = 8$, $\psi(1) = 1$, $\psi(0) = 0.01$. Assume also that Λ_1, Λ_2 are independent and equally likely to be 0,1.

$$\Delta^* = \frac{W}{2}$$

$$\mathsf{E} u_f(\lambda_1) \approx \frac{W}{2}$$

$$\mathsf{E} u_s(\lambda_1) \approx 2W, \qquad \text{4 fold increase}$$

$$\mathsf{E} u_d(\lambda_1, \lambda_2) \approx 3W. \qquad \text{additional 1.5 fold increase}$$

Generalization

- The results for two operators and two traffic levels can extend to more general cases.
- Multiple traffic levels: Pure strategy may not exist, but we can construct a mixed strategy.
- Multiple operators: A simple controller is needed to record trading history and generate a mapping among borrowers and lenders.
- All the proposed mechanisms with truth-telling are subgame perfect Nash equilibria.

Conclusion

- Sharing of unlicensed spectrum gives rise to a game theory problem;
- Selfish and strategic operators find that being entirely noncooperative is a Nash equilibrium; yet cooperative sharing is to the best interest of all;
- Mechanisms have been designed such that operators seek a subgame perfect Nash equilibrium where all operators are fully cooperative;
- The results encompass entry barriers, externalities, and present value of revenues.
- Recommendations to the wireless industry:
  - The said subgame perfect Nash equilibrium provides the fundamental basis for all operators/equipment makers to form consensus;
  - The said equilibrium could be a goal of an LTE-U standard;
  - To avoid the tragedy of commons and the vulnerability of WiFi, the LTE-U standard should perhaps include real mechanism to punish deviators.
- Ongoing work: 1) WiFi/LTE-U coexistence; 2) market share competition.

Positions of some major players

- There is broad concensus that licensed spectrum is superior; LTE-U does not reduce or dilute the need for licensed spectrum;
- Nokia: simple methods enable fair band sharing between WLAN and LTE-U. Still, better to use separate channels;
- Israeli Assoc. of Electronics & Software Industries (IAESI): channel sharing based on energy detection is bad for both 802.11 and LTE-U.
- NTT Docomo: Coexistence with WiFi needs to be carefully studied.
- Samsung: UE will have to implement two technologies for the same spectrum; decrease the value of current licensed spectrum? QoS?
- Broadcom: Regional LTE-U technology bad for everybody; LTE-U must address the global market; 5 GHz band is not greenfield spectrum—regulatory aspects to be studied;
- Sony object opportunistic regional deployment of LTE in 5725–5850 MHz;
- AT&T: LTE-U should not negatively impact existing services; peaceful coexistence with WiFi is required; comprehensive protection assessment a must; globally inclusive; LTE-U should not have adverse impact on future licensed spectrum allocation.

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