Collective subscriptions: a novel funding tool for crowdsourced network infrastructures

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https://mm.aueb.gr/crescendo/mkaralio.html

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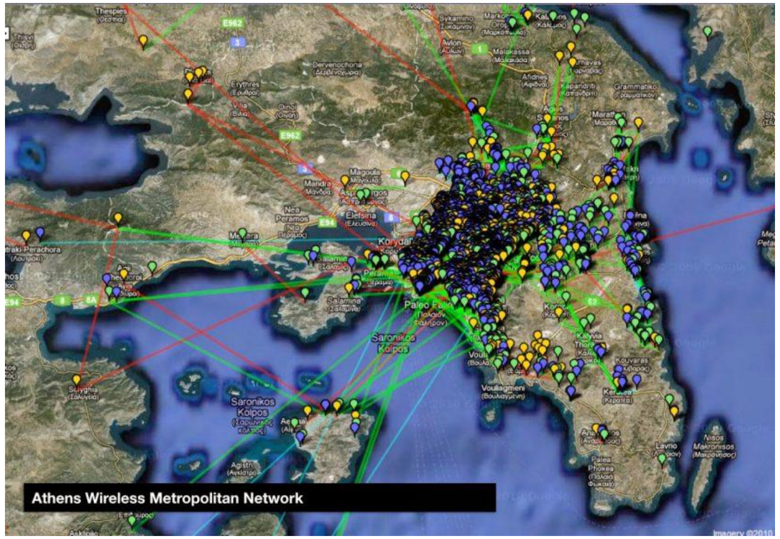
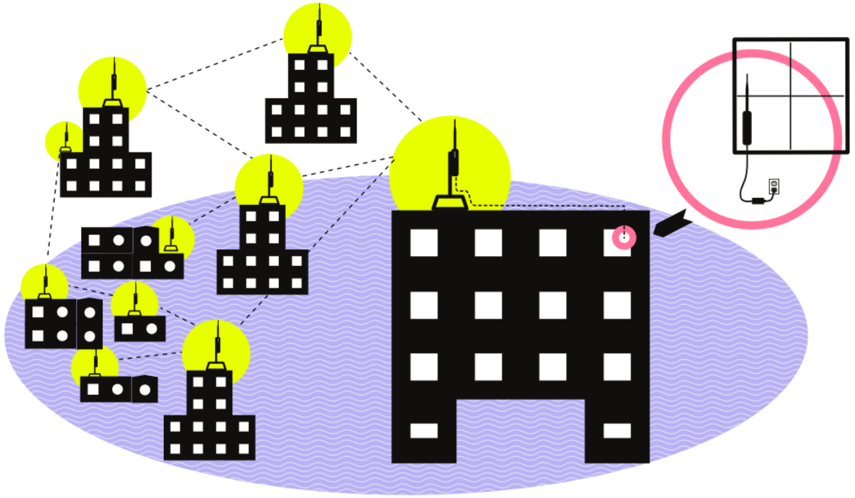
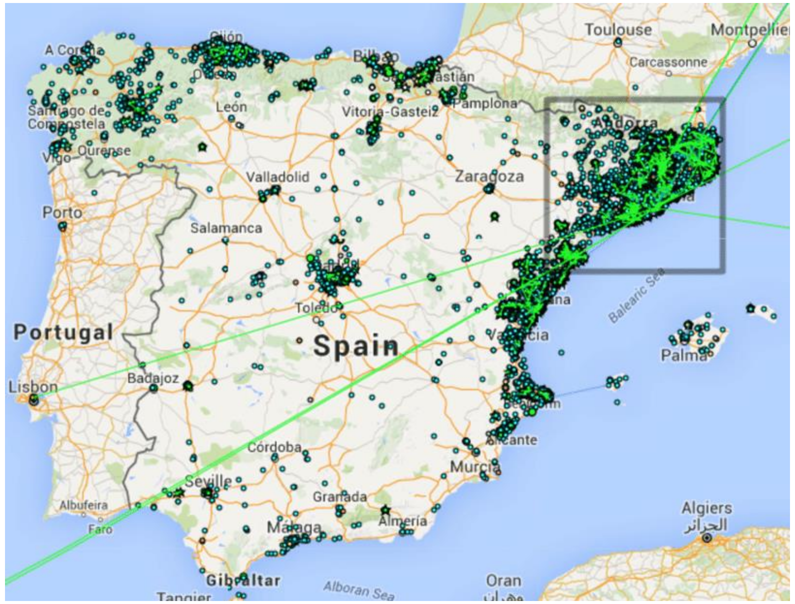
Community Networks worldwide : a 20-year long story

- grassroots initiatives in both urban and rural areas
- addressing a broad mix of needs
  - experimentation with technology and DIY, digital divide, autonomy and community ideals



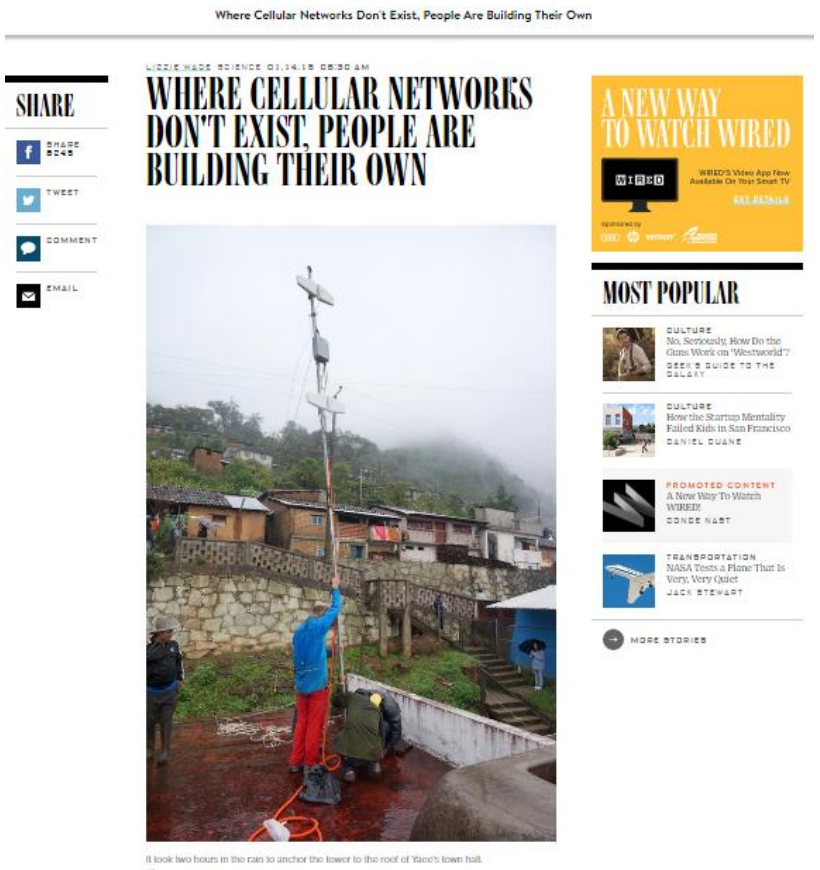




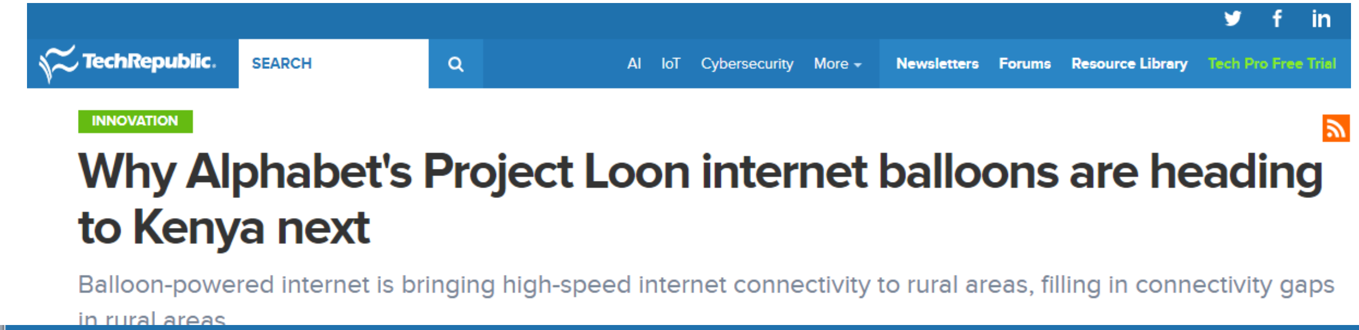
Three good reasons for renewed interest in CNs

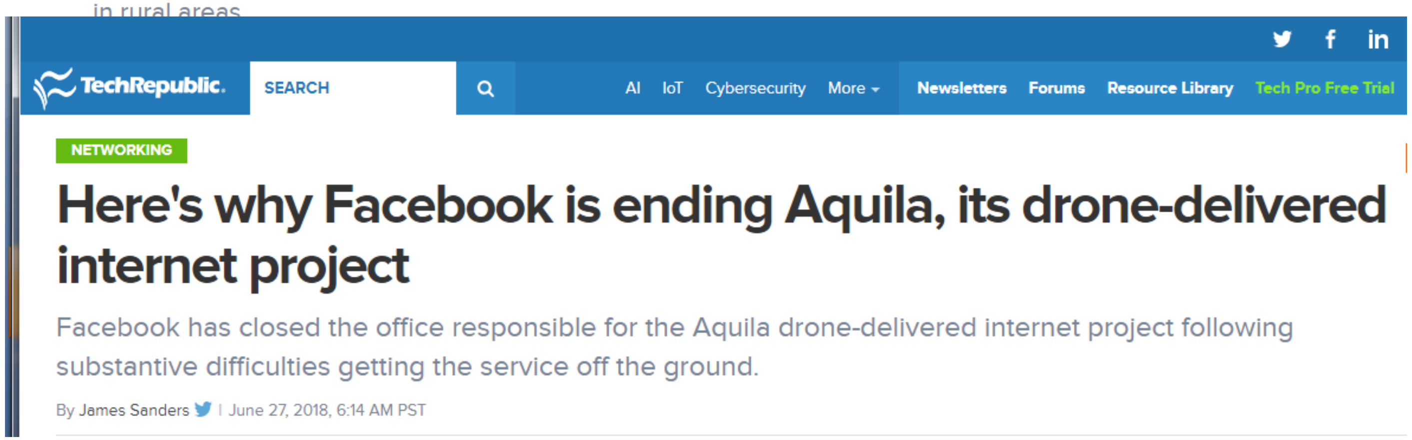
1. Bridging the digital divide- connecting the next billion of people

- the "local" bottom-up approach to the problem



- …as opposed to ambitious global top-down approaches to the problem

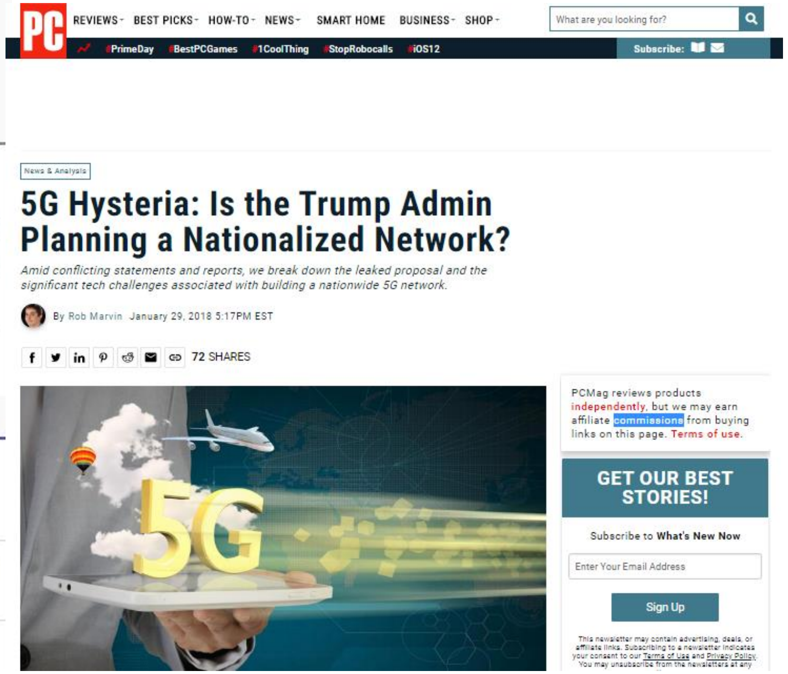




Three good reasons for renewed interest in CNs

2. Enabling broadband connectivity agendas: CNs as network infrastructure providers

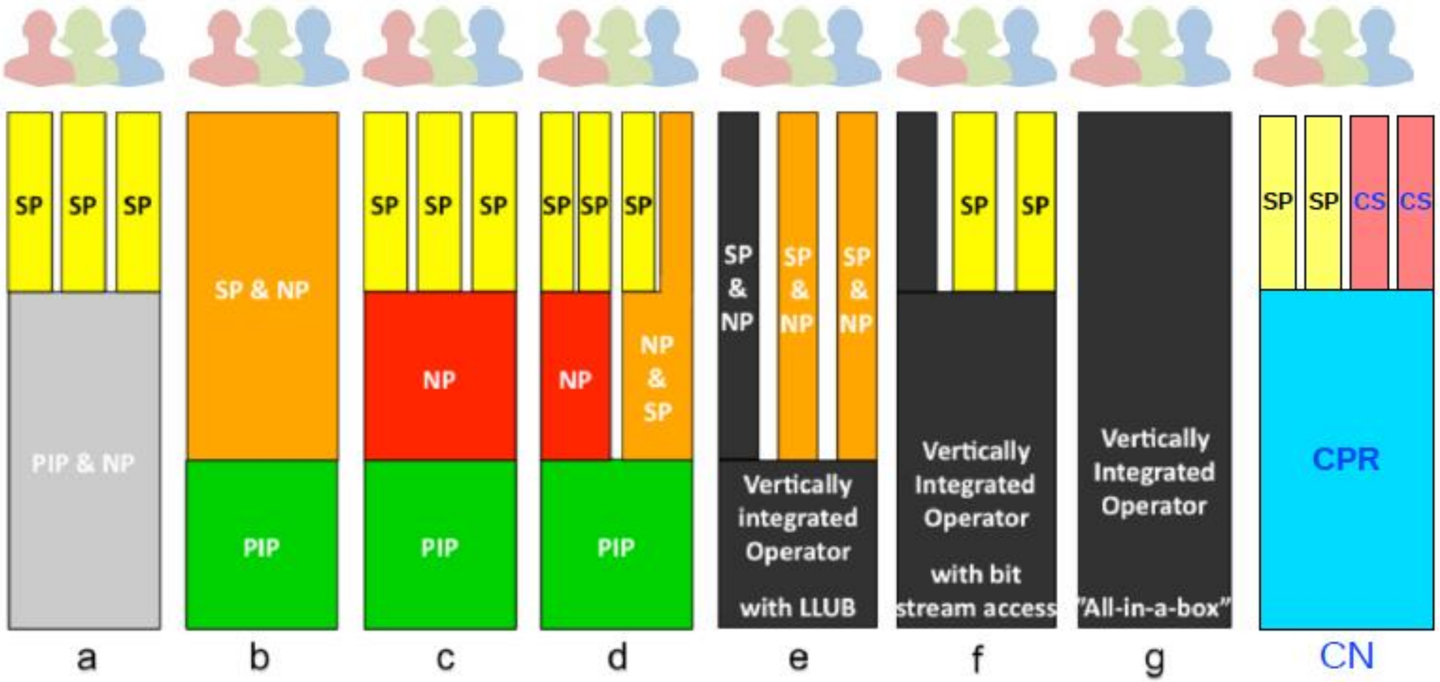
- e.g., Broadband Europe 2020 and 2025 or 5G mobile systems

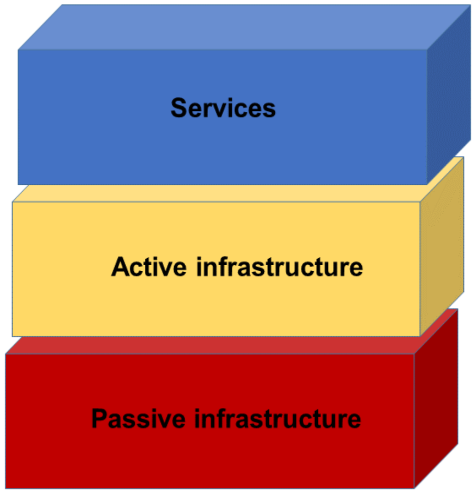


Three good reasons for renewed interest in CNs

3. Democratizing the market

- through fostering more open telecom network models against dominant trends for verticals





Economic sustainability of CNs

CN expenses

Capital expenses (CapEx)

- Equipment: access points, routers, antennas, servers
- Installation costs
  - Mounting antennas and access points
  - Digging costs (when deploying fiber)

Operational expenses (OpEx)

- Cost of peering agreements for Internet access (leased lines)
- Maintenance of network nodes
- Software for network management, network monitoring, billing
- Electricity costs

CN revenue sources

- Donations from supporters

  crowd-funding, regular or one-time donations, investments in the infrastructure

- Support from public agencies and institutions

  public funds from municipalities or local authorities, grants from non-profit institutions

- Funding from private sector

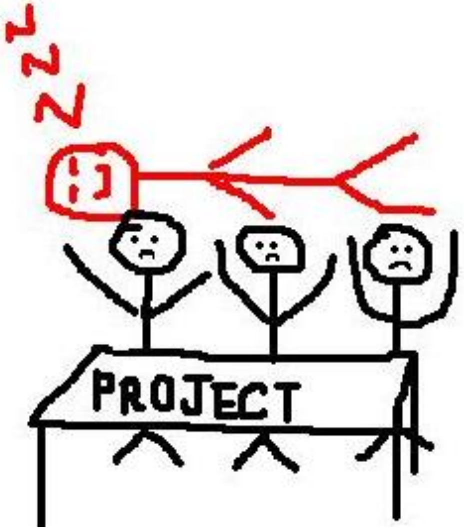
  synergies with commercial for-profit service providers under commons-based policies

- Member subscriptions
  - monthly or yearly
  - All CN success stories rely on their members' subscriptions

Individual subscriptions and free riding

The de-facto subscription scheme is fixed-price subscriptions. The subscription fee

- one the one hand, should maximize inclusion of the community
- on the other hand, should secure sufficient revenue for the CN economic sustainability



Not always an easy task:

- **free riding** is frequent in these CNs, not least due to affordability

Toy example : 5 users who can afford *15, 13, 12, 8, 5 Euros per month,* respectively, for a subscription.

If the subscription fee f_s is set to:

$f_s \leq 5$, all five users can join, paying up to 5 each → CN revenue up to 25 Euros

$5 < f_s \leq 8$, the first four users can join, paying up to 8 each → CN revenue up to 32 Euros

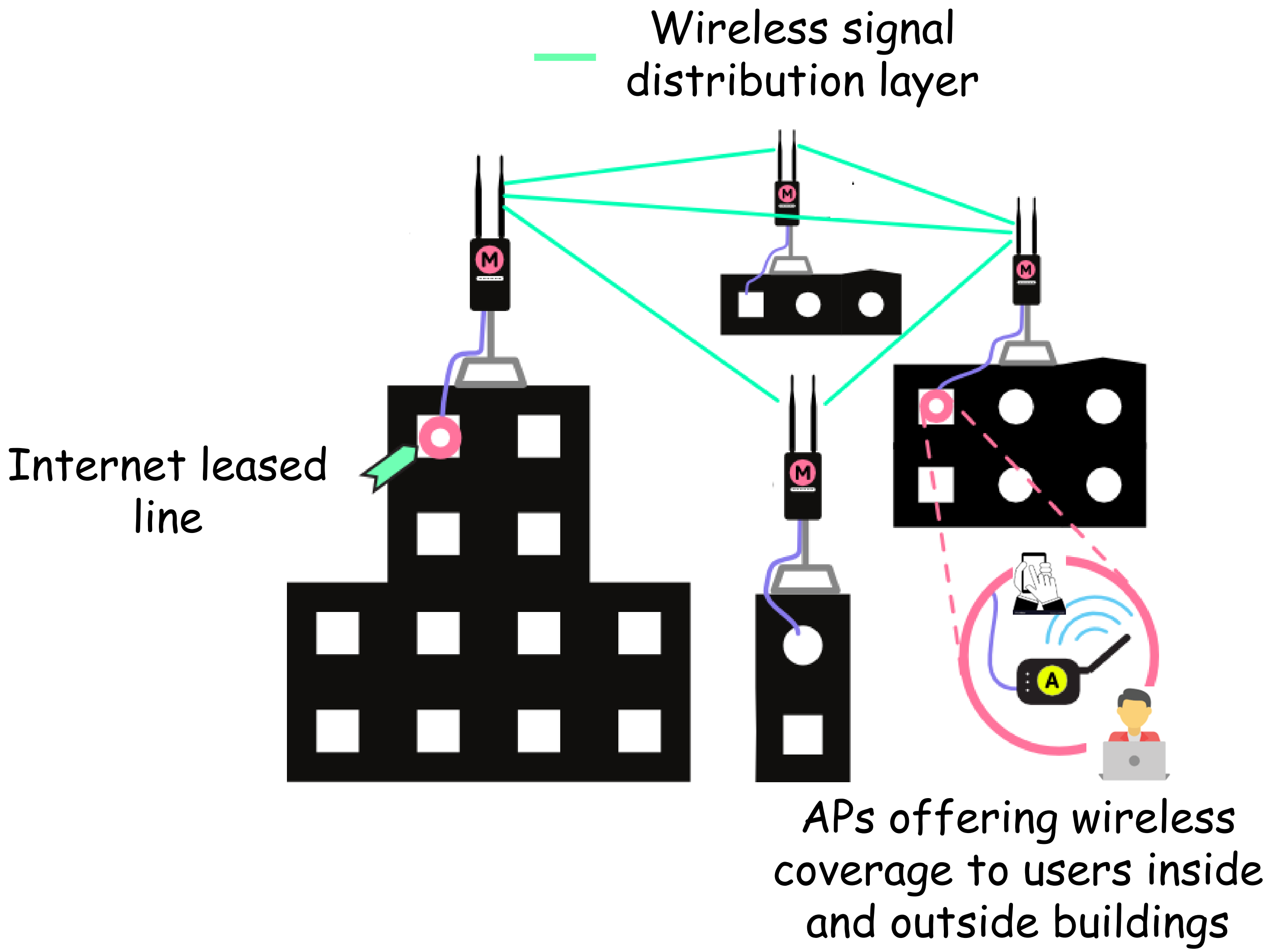
$8 < f_s \leq 12$, the first three users can join, paying up to 12 each → CN revenue up to 36 Euros

Collective subscriptions - outline

- **Idea :** instead of charging individual CN users, charge the CN node owners *only* and share the subscription costs with users subscribing to the node
  - attempt to accommodate the varying amounts users are willing to pay for membership and connectivity

- **Outline of the remainder of the presentation**
  - the collective subscriptions optimization problem
    - system model, assumptions, problem formulation, characterization in the general case
  - solution of the problem
    - structural properties, enumerative algorithm over a reduced search space
  - evaluation of the scheme
    - performance characteristics, comparison with fixed-price individual subscriptions

System model - actors



The illustration is a processed version of a graphic at https://commotionwireless.net

Set of users, *U*

- assess differently the Internet connectivity value → individual **price ceilings** r_j , $j \in U$
- each user u prefers to join the subscription of a certain set of CN nodes N_u out of the full CN node set N
  - e.g., those she uses most frequently, close to her house or neighborhood

CN operator, CNO

- sets the node subscription fee f_s and distributes users to node subscriptions
- seeks to maximize revenue but also let as many as possible join the CN

Collective subscriptions: three assumptions/properties

- No discrimination at node subscription level — ASS1
  - the fee f_s charged by the CNO is common for all CN nodes

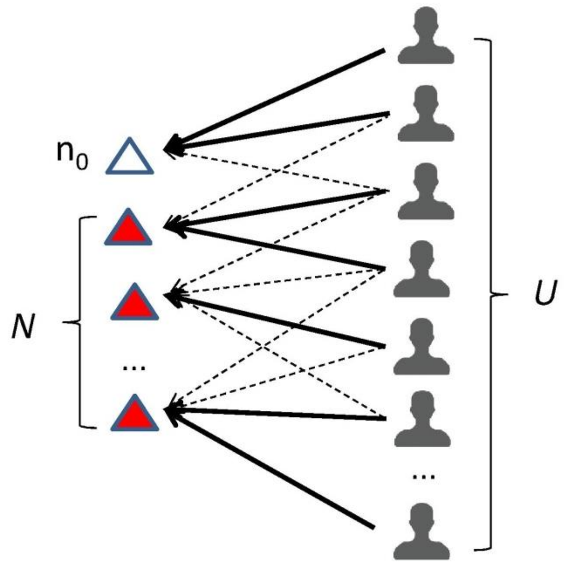
- No discrimination at user level *within a given node* — ASS2
  - if *k users* join a node subscription, the fee share each one pays is f_s/k
  - however, users assigned to different nodes may end up paying different amounts
    - the more users join a CN node subscription, the less the fee share for each user (positive externality)
    - ⇒ an incentive for CN node owners to recruit more users

- The CNO is aware of the true price ceilings of users — ASS3
  - the strongest assumption (and the main subject of current follow-up work)

Optimizing collective subscriptions

Let $P = (p_0, p_1, p_2, \dots, p_N)$ be a partition of CN users to the N nodes

- $k_n = |p_n|$, the number of users joining the subscription of node n
- p_0 : set of users who do not join the CN (they cannot afford the fee)
- α : an upper bound on the number of users who cannot afford the subscription



Then:

- The maximum fee the CNO can collect out of node *n* is : $fee(n) = k_n \min_{u \in p_n} r_u$
- The total fee that the CNO can collect out of the CN is : $R_{CNO}(p) = \min_{\substack{n \in N \\ k_n > 0}} fee(n) \cdot \sum_{n \in N} 1_{k_n > 0}$
- The objective of CNO is to

$$\max_p \; R_{CNO}(p) \qquad (OPT)$$

$$s.t. \quad k_n = \sum_{u: n \in N_u} x_{un} \quad \forall n \in N \cup n_0$$

$$\sum_{n \in N_u \cup n_0} x_{un} = 1 \qquad \forall u \in U \qquad \text{assignment constraints}$$

$$k_0 \leq \alpha \qquad \text{inclusion constraint}$$

$$x_{un} \in \{0,1\} \;\; u \in U, n \in N \cup n_0$$

Problem characterization

The problem (OPT) is NP-hard in the general case

- non-identical user price ceilings
- non-identical user subscription preferences (distinct sets N_u)

The problem simplifies under special cases

- identical user price ceilings ($r_u = r_v = r \ \forall u,v \in U$)
  - the problem reduces to a special case of the restricted max-min fair allocation problem
- identical user price ceilings **and** subscription preferences ($N_u = N$)
  - trivial solution to the assignment problem
- identical user subscription preferences ($N_u = N$), equivalently: user indifference to the subscription assignment
  - …see the remainder

Collective subscriptions : identical user subscription preferences

Idea : enumerate possible solutions albeit in a significantly reduced search space

Definition : $r - ordered\ partition\ \ p_{ord}(k_0, k_1, k_2, \dots, k_N)\ with\ k_j \geq k_{j+1},$ j∈[1..N-1]

The single partition *p* (of users to node subscriptions) out the set of all partitions $P(p_0, p_1, p_2, \dots, p_N)$ such that

- $|p_j| = k_j,$ j∈[1..N]
- $\max_{u \in p_j} r_u \leq \min_{u \in p_{j+1}} r_u$, j∈[1..N-1]

<u>Example</u>: $\mathrm{N} = 4, \mathrm{U} = 13, \overline{r} = [2,3,3,5,6,7,8,10,12,14,15,15,16]$

Then:

$$p_{ord}(1,4,3,3,2) = \{\{2\}, \{3,3,5,6\}, \{7,8,10\}, \{12,14,15\}, \{15,16\}\}$$

$$p_{ord}(1,5,4,2,1) = \{\{2\}, \{3,3,5,6,7\}, \{8,10,12,14\}, \{15,15\}, \{16\}\}$$

$$p_{ord}(0,5,4,2,2) = \{\emptyset, \{2, 3,3,5,6\}, \{7,8,10,12\}, \{14,15\}, \{15,16\}\}$$

Collective subscriptions : identical user subscription preferences

Proposition : Any partition $p(k_0, \sigma(k_1), \sigma(k_2), \ldots, \sigma(k_N))$, where σ is an arbitrary permutation of the set $\{k_1, k_2, \ldots, k_N\}$, can be converted to an r − ordered partition $p_{ord}(k_0, k_1, k_2, \ldots, k_N)$ so that

$$R_{CNO}(p) \leq R_{CNO}(p_{ord})$$

<u>Example:</u>

arbitrary partition (1,4,3,3,2)

p_0	p_1	p_2	p_3	p_4
3	5	6	15	2
	15	7	12	10
	8	16	3	
	14			

$R_{CNO} = 12$

Algorithm 1 Transformation of an arbitrary partition to its r-ordered counterpart

Input: Partition subset p_0 and subsets $p_1,..,p_N$, indexed in order of decreasing cardinality

Output: Subsets p_0, $p_1,..,p_N$ of the r-ordered partition

```
for every subset j ∈ [0..N − 1] do
    z = max value in subset j, w = min value over subsets
    indexed in [j+1..N-1], m = subset hosting w
    while w < z do
        move z to the subset m and w to p_j
        z = max value in subset j, w = min value in subsets
        indexed in [j+1..N-1], m = subset hosting w
    end while
end for
```

r-ordered partition (1,4,3,3,2)

p_0	p_1	p_2	p_3	p_4
2	5	10	15	16
	3	7	12	15
	6	8	14	
	3			

$R_{CNO} = 48$

Collective subscriptions : identical user subscription preferences

Corollary: To find the the optimal partitions of end users to CN node subscriptions, it suffices to search through the set of r − ordered partitions featuring $k_0 \leq a$

- search complexity becomes polynomial $O(N^U)$ instead of exponential $O(U^N)$ to the number of users (note that typically U >> N)

Evaluation of the scheme

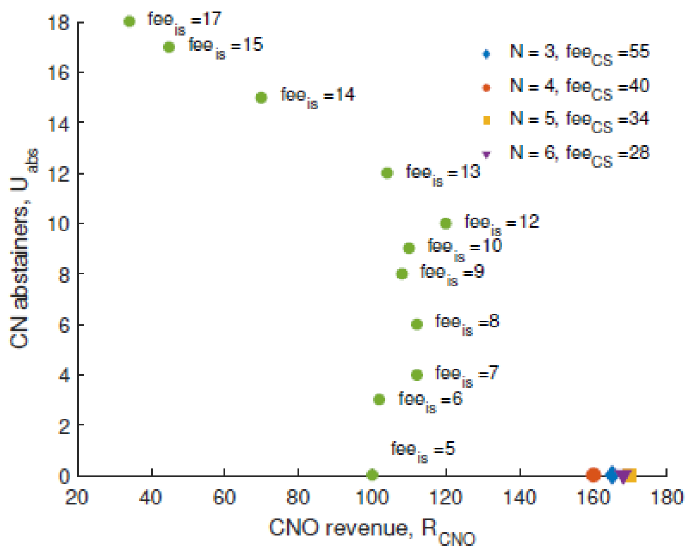
Main questions

- How well can collective subscriptions trade off community inclusion (number of abstainers, U_{abs}) with achievable revenue (R_{CNO})?
  - How do they compare in this with fixed individual subscriptions?
- What other variants of the scheme are possible?

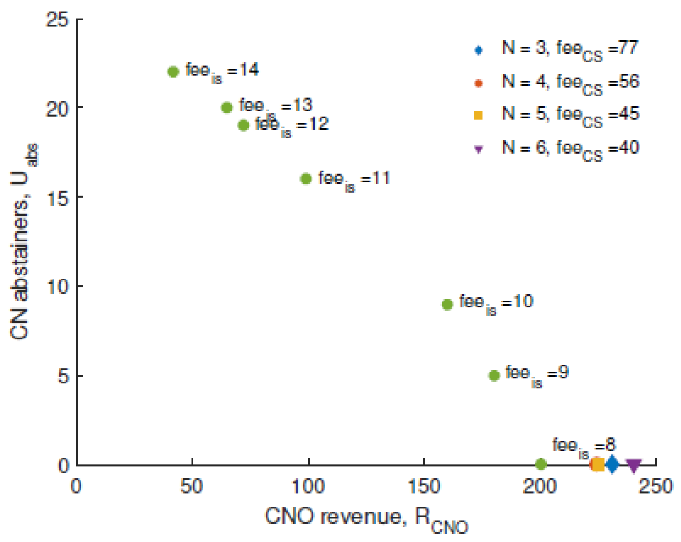
Methodology

- Get (N,U) pairs from real data (drawn from a Greek rural CN) or generate synthetic data
- Synthetic distributions for price ceilings, $r_u \in \{r_{min}..r_{max}\}$

Collective *vs.* individual fixed price subscriptions



$U = 20, r \sim U\{5,17\}$



$U = 25, r \sim U\{8,12\}$

- Solve OPT with α = 0 (include everyone in the CN)
- Collective subscriptions consistently achieve higher revenue than individual subscriptions
  - even if users with low price ceilings are excluded from the CN
  - CNO revenue gains range from 12.5% to 43% across experiments

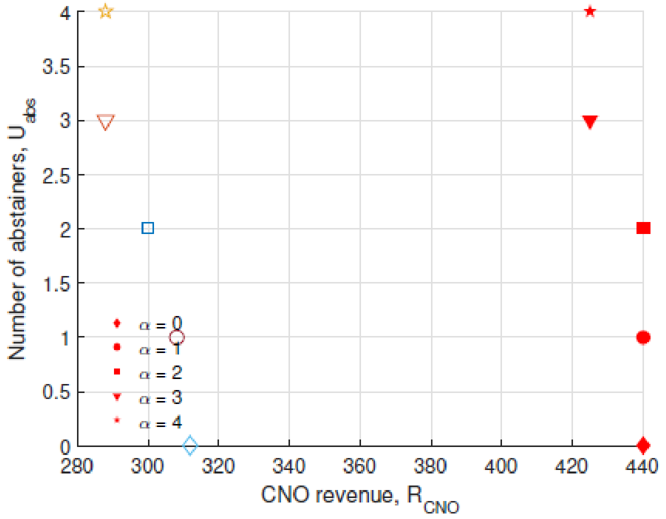
Does this experimental evidence generalize?

Proposition : For any given set of users and their corresponding price ceilings, collective subscriptions yield (R_{CNO}, U_{abs}) *values* that Pareto − dominate those obtained under fixed price individual subsriptions

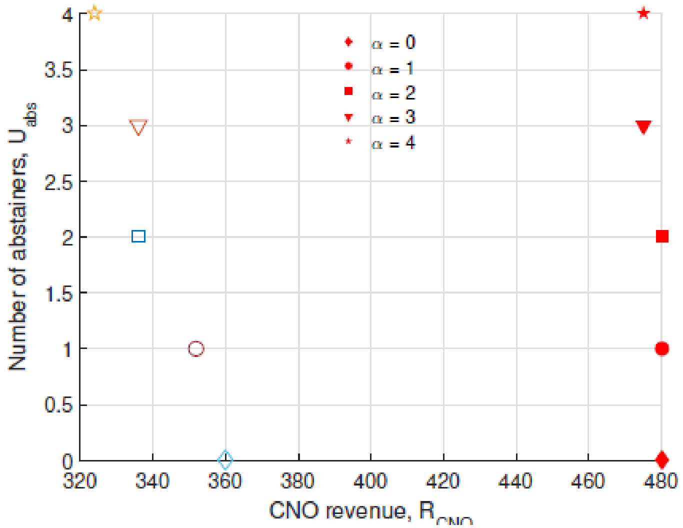
- upon the condition that $\mathrm{U} - U_{abs} = \delta \cdot \mathrm{N}, \delta \in \mathrm{Z}^{+}$
- there are (rare, quite extreme cases) that proposition does not hold, i.e., when U is prime and $r_u = r_v \ \forall u, v \in U$

Revenue vs. community inclusion under collective subscriptions

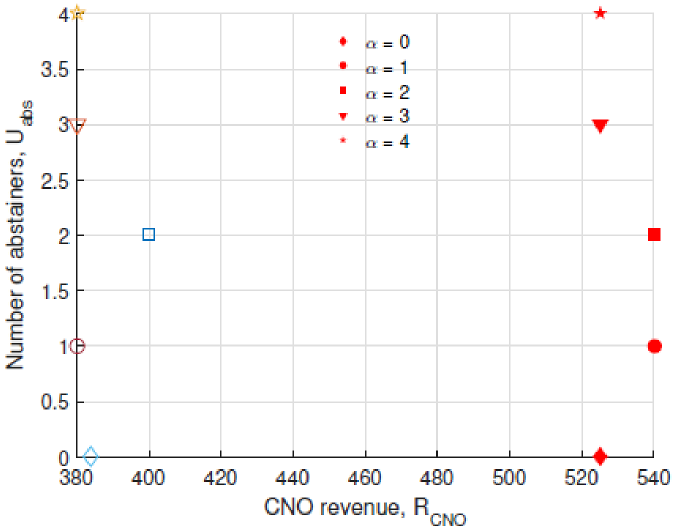
Filled markers correspond to (U = 40, N = 5). Empty ones correspond to (U = 30, N = 4).



$r \sim \{8,14\}$ for 80% of users



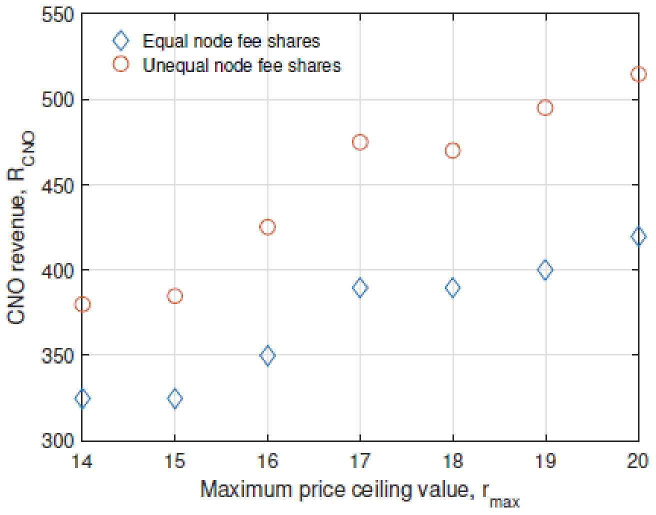
$r \sim U\{8,20\}$



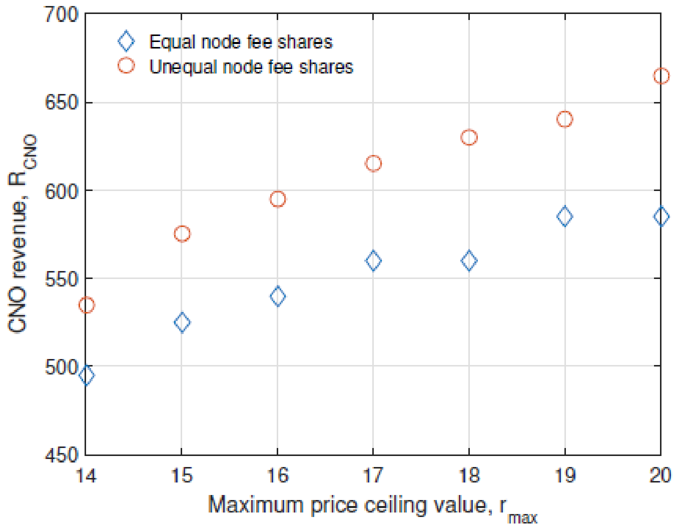
$r \sim \{8,14\}$ for 20% of users

- Solve (OPT) with the inclusion constraint turned to equality ($k_0 = a$)
- For uniform (middle plot) and positively skewed distributions (left plot) of user price ceilings revenue and participation are simultaneously maximized
- Under negative skew, the revenue may increase when excluding a few users with the lowest price ceilings

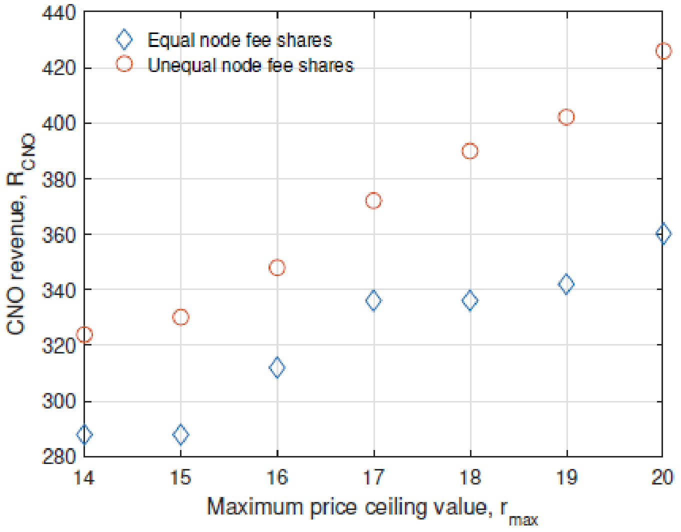
Collective subscriptions with unequal node subscription fee shares



$U = 40, N = 5, rmin = 5$



$U = 50,\ N = 5, rmin = 8$



$U = 30,\ N = 6, rmin = 8$

- Solve a modification of OPT with $fee(n) = \sum_{u \in p_n} r_u$ and *a = 0* → *multi-way partitioning problem*
- The revenue is consistently higher when the node subscription fee sharing becomes more flexible
  - gains in the order of 10% to 25%
  - on the downside, the introduced discrimination among users who share the subscription of the same node strengthens the motivation to misreport the price ceilings

Concluding and the way forward

- We have proposed an innovative subscription mechanism for community networks to self-fund their activities and took some steps in analyzing it
  - the mechanism matches well the strong sharing ideals of these crowdsourced infrastructures

- The mechanism demonstrates a clear performance advantage over fixed-price individual subscriptions
  - resulting in higher revenue for the CNO and better inclusion of the end users
  - serves as incentive for recruiting more members to the CN and sharing the subscription cost

- The strongest assumption that has to be relaxed is that end users declare truthfully what they are willing to pay for Internet access
  - users are tempted to underbid in the expectation that they will end up with lower cost shares, possibly at the expense of other users
  - we currently explore how to shape collective subscriptions into a mechanism that induces truthfulness as an equilibrium

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