Outline

Introduction

System Model and Problem Formulation

Throughput Optimal Routing and Scheduling

Near-optimal throughput in presence of finite energy storage
Introduction

- Research interest in wireless systems and networks that are powered by renewable energy sources like solar, wind, vibration, etc.
- has advantages in terms of operation cost and environment-friendliness, and in many cases may be the only option available due to practical constraints.
Examples

Figure: meraki, with solar panels
Examples

Figure: meraki, network deployment
**Figure**: proxim wireless, others. Application: backhaul, surveillance, etc.
Examples

Figure: wind micro-turbines
Examples

Figure: mechanical vibration to electric energy
Also desirable to minimize cost and environmental hazards to draw energy from non-renewable sources only when the amount of available renewable energy is not enough.

*wireless* eventually should mean no dependence on power line or battery replenish.
Objective

- Delivering (as much as possible) data packets from sources to their destinations
- Subject to availability of energy in the storage
Challenges

- Rate of renewable energy generation is small, implying energy is a constraint
  - Solar panels $\rightarrow$ tens of watts $\rightarrow$ WiFi Access Points
  - Micro-turbines/vibration $\rightarrow$ m or $\mu$-w $\rightarrow$ small sensors
- Temporal availability (arrival) of non-renewable energy is subject to random environmental factors and hence stochastic, neither controllable nor accurately predictable
- Limitation in the energy storage capacity
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Insight

- Our utility is flexible over time, as long as the long term averages are optimized
- Energy decisions and network decisions be decoupled
Contribution

- design of joint routing and scheduling algorithms that are stochastically optimal, in the sense that they maximize end-to-end data throughput in the network. under very loose assumptions on the stochastic behavior of the energy replenishment processes at the network nodes.

- our algorithms do not need to know the energy replenishment rates, and can dynamically learn and adapt to their variations.

- Also do not require a priori knowledge of the data traffic generation rates, and achieve the maximum throughput region
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- obtain bounds on the capacity of the energy storage devices at the individual nodes that is minimally required to attain maximum throughput

- what fraction of the maximum throughput region can be attained when the energy storage capacity is less than this limit
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a multi-hop wireless network modeled as a directed graph \( G = (V, E) \), where \( V \) and \( E \) respectively denote the sets of nodes and links, and \(|V| = N, |E| = L|\).

The network has \( M \) sessions, or end-to-end flows, \( 1, \ldots, M \). Each session refers to a source(s)-destination(s) pair.
System Model and Problem Formulation

- $A_m(t)$: the number of packets that session $m$ generates at its source node in interval $(t, t + 1]$, $m = 1, \ldots, M$.

- We assume that the arrival process $\{A_1(.), \ldots, A_M(.)\}$ is stationary, ergodic with $\mathbb{E}(A_m(t)) = \lambda_m$, where $\lambda_m$ is referred to as the packet arrival rate of session $m$, and $A_m(t) \leq \gamma$ for each $m, t$ for a constant $\gamma$.

- no preset routes in the network, and different packets may follow different routes depending on network congestion and energy availabilities at different nodes which also vary with time.
System Model and Problem Formulation

- $E_i(t)$: the number of energy units that node $i$ generates in interval $(t, t + 1]$, $i = 1, \ldots, N$.
- $\mathbf{E}(E_i(t)) = e_i$, where $e_i$ is referred to as the energy arrival rate of node $i$.
- The energy arrivals at different nodes may be correlated.
- The packet arrival rate vector $\vec{\lambda}$ and energy arrival rate vector $\vec{e}$ are $M$- and $N$-dimensional vectors of the packet and energy arrival rates.
Node $i$ can store at most $B_i$ units of energy, and generated energy is lost if the storage is full.

Node $i$ consumes $t_i$ ($r_i$, resp.) units of energy when it transmits (receives) a packet.

Let $C_i(t)$ be the number of energy units used up by $i$ in interval $(t, t + 1]$, $i = 1, \ldots, N$, and $P_i(t)$ be the number of energy units available at node $i$ at time $t$. Thus, the energy queue, $P_i(t)$ evolves as:

$$P_i(t + 1) = \min (B_i, P_i(t) + E_i(t) - C_i(t)).$$
When a link is scheduled for transmission, it transmits a packet, and energy is consumed at its origin and end nodes.

A *schedulable set* of links is a subset of its links such that all links in the subset can be scheduled simultaneously.

Let $J_1, \ldots, J_K$ be the schedulable sets and let $\vec{J}_i$ be the $L$-dimensional indicator vector representing any schedulable set $J_i$. Let $\mathcal{J} = \{J_1, \ldots, J_K\}$. Any subset of a schedulable set is also a schedulable set.
System Model and Problem Formulation

- A *routing and scheduling policy* is an algorithm that decides in each slot the subset of links that would transmit packets in the slot and the sessions these packets belong to.

- A scheduling policy must designate sessions at each node and subsequently, select an element of $J$ in each slot, and this element must be such that all links in it have packets to transmit and the sources and sinks of the links in it have the requisite amount of energy for packet transmission and reception.
Let $D_i^m(t)$ be the number of packets that link $i$ transmits from session $m$ in interval $(t, t + 1]$, $i = 1, \ldots, N$.

Let $Q_{mu}(t)$ be the number of packets of session $m$ that are waiting for transmission in node $u$ at the beginning of slot $t$.

We assume each packet queue has infinite storage.

Note that the arrivals at a node happen due to exogenous packet generation, and also because of transmission on input links to $i$. Thus,

$$Q_{mi}(t + 1) = Q_{mi}(t) + A_i^m(t) + \sum_{i \in I_u} D_i^m(t) - \sum_{i \in O_u} D_i^m(t).$$
The network is said to be stable if
\[
\lim_{T \to \infty} \sum_{m=1}^M \sum_{i=1}^N \sum_{t=1}^T \mathbb{E}(Q_{mi}(t)) / T
\]
is finite.

The stability region of a scheduling policy is the set of packet and energy arrival rate vectors for which the network is stable when the policy is used.

A pair of packet and energy arrival rate vectors \((\vec{\lambda}, \vec{e})\) is said to be feasible if it is in the stability region of some scheduling policy.

The network stability region is the set of all feasible pair of packet and energy arrival rate vectors.
The necessary conditions for a pair \((\vec{\lambda}, \vec{e})\) to be feasible is that there exist fractions of time \(\omega^m_J\) associated with the independent sets \(J\) and session \(m\) such that:

\[
\sum_{J \in J} \omega^m_J \left( |J \cap O_v| - |J \cap I_v| \right) = \lambda^m_v, \quad \forall \ v \in V, \quad (1)
\]

\[
\sum_{J \in J} \sum_{m \in M} \omega^m_J \left( t_v |J \cap O_v| + r_v |J \cap I_v| \right) \leq e_v, \quad \forall \ v \in V, \quad (2)
\]

\[
\sum_{J \in J} \omega^m_j \leq 1; \quad \omega^m_j \geq 0, \quad \forall \ J \in J, \quad (3)
\]
We will show that for large energy storage capacities the above conditions also become sufficient as well, when the equality and inequality in the first two conditions are replaced by strict inequalities. Thus, we will consider packet and energy arrival rate pairs that satisfy:

\[ \sum_{J \in J} \omega^m_J \left( |J \cap O_v| - |J \cap I_v| \right) \geq \lambda^m_v + \delta, \quad \forall \ v \in V \]  
\[ \sum_{J \in J} \omega^m_J \left( t_v |J \cap O_v| + r_v |J \cap I_v| \right) \leq e_v - \varepsilon, \quad \forall \ v \in V, \]  

for some positive \( \delta \) and \( \varepsilon \) fractions \( \{ \omega^m_J \} \) that satisfy (3).
First consider the case of $t_v = 1$, $r_v = 0$, $B_i = \infty$ for all $i$.
Under these idealized assumptions, we describe a routing and scheduling policy that does not require any knowledge of the packet and energy arrival rate vectors, and prove that it stabilizes the network for any packet and energy arrival rate in $\Lambda_{\delta,\varepsilon}$ for any positive $\delta, \varepsilon$. 
The policy consists of two key steps.

- **Energy Marking**
- **Packet Transmission**
Energy Marking:

- Each node consists of two (virtual) buffers: *entry buffer* and *exit buffer*.
  - In each slot, consider nodes at which energy buffer has at least one unit of unmarked energy.
  - Select the pair which has the largest surplus of backlogs between the input buffer and the output buffer, provided that this value is strictly positive.
  - Among such queues (each corresponding to a unique session), one queue is selected (say at random) from which one packet is transferred from the entry buffer to the corresponding queue in the exit buffer.
  - Simultaneously, 1 unit of energy in the energy buffer is marked for this packet. The packet now awaits transmission in one of the output links, and the marked energy unit will be used for transmitting the packet whenever the transmission process occurs.
Throughput Optimal Routing and Scheduling

Figure: Packet buffering and energy marking at each node (for negligible reception energy cost, i.e., $r_v = 0$). If $r_v > 0$, an intermediate buffer and per-link exit buffers are needed.
Throughput Optimal Routing and Scheduling

The marking is a logical step, and ensures that the node has enough energy to transmit each packet in its exit buffer, and thus transmissions can be scheduled from this buffer without considering energy availability any further.
Packet Transmission

- Let $Q_{mu}(t), Q_{mu}(t)$ denote the queue lengths of session $m$ at the exit and entry buffers at each node $u$.

- The weight of each link $(u, v)$ is the largest difference between the queue lengths at the exit buffer of $u$ and the entry buffer of $v$ amongst different sessions, $\max_m (Q_{mu}(t) - Q_{mv}(t))$.

- The weight of a schedulable set is the sum of the weights of the links in the set.

- At any slot, the schedulable set with the maximum weight (and minimum size amongst all those with the maximum weight) is found and each link in that set transmits a packet.
The energy marking step is localized and as a result no node needs to know of other nodes’ energy availabilities.

The packet transmission step is in general a high complexity procedure (corresponds to an maximum weight independent set problem in general) due to the global nature of the interference constraints.

For certain forms of “local” interference constraints, it can be implemented or approximated in a distributed manner, with low message complexity and provable approximation guarantees.
The packet transmission step not only selects the sessions and schedules links, but also selects routes for the packets of a session by determining which links they would follow in the immediate next step.

The routing depends on both congestion and energy availability in an implicit manner.
Theorem

If \((\bar{\lambda}, \bar{e}) \in \Lambda_{\delta, \varepsilon}\) for some positive \(\delta, \varepsilon\), the Energy Back-pressure policy stabilizes the network.
Theorem

For $\lambda \in \Lambda_{\delta, \epsilon}$ and under the no-loop routes assumption\(^1\), the expected delay attained by our policy is at most 
\[
\frac{((4 + 2\gamma)N + 3 + \gamma)}{4\delta}.
\]

\(^1\)that the routes are preset for each sessions and are such that there is no loop on paths from any source to its destination.
When nodes consume different amounts of energy for transmissions, i.e., $t_v$ differs across nodes, a necessary condition for transferring a packet to the exit buffer at $v$ is that $v$ has at least $t_v$ amount of unmarked energy and such a transfer leads to marking of $t_v$ energy units at $v$. All results hold.
Generalizations

When reception energy cost $r_v$ is non-negligible, the packet buffering policy has to be altered slightly:

- Each node $u$ maintains one entry buffer as before, but one intermediate buffer and one exit buffer for each of its outgoing links.
- A packet is transferred from the entry buffer to the intermediate buffer and $t_v$ energy units are marked for usage at $u$ if:
  - $u$ has at least $t_v$ units of unmarked energy (including new energy arrivals), and
  - the intermediate buffer at $u$ has fewer packets than the entry-buffer.
Generalizations

- A packet is transferred from the intermediate buffer to an exit buffer and only if
  - the end-node of the corresponding outgoing link has at least $r_v$ units of unmarked energy, and
  - the exit buffer has fewer packets than the intermediate buffer
- $r_v$ energy units are marked at this end-node
- Note that this step requires a node to communicate with its next hop (unlike the case where only transmission energy cost is considered), but such message exchange is still “local”.
Finite-storage Energy Back-pressure policy

Finite-storage Energy Back-pressure policy We describe how finite storage energy back pressure policy differs from its infinite storage version:

- The energy marking storage step is the same except that a packet at the entry buffer of node $v$ is transferred to the exit buffer if $v$ has at least one unit of unmarked energy and the exit buffer has fewer than $B$ packets (note that a packet may be transferred even if the entry buffer has fewer packets than the exit buffer).

- The packet transmission step is the same except that the weight of link $(u, v)$ at time $t$ is $Q_u^o(t)Q_u^i(t) - BQ_v^i(t)$. 
Theorem

If \( (\bar{\lambda}, \bar{e}) \in \Lambda_\delta \) and \( B \geq 4/\delta \), the Finite-storage Energy Back-pressure policy stabilizes the network.
Thank You!

Questions/Comments