Energy-efficient Machine-To-Machine Communications:
State of the art, challenges and directions

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What is an M2M Network?
Why M2M Networks?

Data flow between subscriber stations and BSs in a cellular network by eliminating the human interaction

Internetworking of M2M Networks

 Millions of M2M devices

Internet of Things (IoT)

• Application areas:
  • Healthcare
  • Smart Grid
  • Metering services
  • etc
Challenges in M2M Networks

- Subscription control for M2M devices
- Overload control on the BSs due to massive access by the M2M devices
- Energy-efficiency
  - Not a major concern in conventional cellular networks
  - M2M devices run on batteries
  - M2M network reliability is dependent on the battery lifetime

Recall: Most critical requirements for the IoT
- Low delay
- High reliability
- Low-power operation
Energy-efficiency in M2M Networks

- Energy efficient....
  - Massive access control
  - Resource allocation
  - Relaying
  - Reporting
  - Routing
    - QoS-guaranteed routing
    - Routing & channel scheduling
    - Retransmission-aware routing
  - Sleep scheduling
  - Harvesting
  - Security
Energy-efficient massive access control

Grouping and coordinator-based solutions

- A single cell with N M2M devices
- Objective:
  - Form $G$ groups minimizing the total energy consumption

Overview:
- Target: M2M core
- Radio Access Network Technology: IEEE 802.16m
- WSN in the M2M device domain
- A centralized solution

Tu et al., “Energy-efficient algorithms and evaluations for massive access management in cellular based machine to machine communications,” VTC-Fall, Sep. 2011
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- Grouping and coordinator-based solutions (Cont ‘d)
  - Grouping constraints

\[ E^j_{i}^{\neq c} = \left[ \frac{S}{(R_{t1}(M^c_i, M^j_i))} \right] \cdot P \quad \rightarrow \quad \text{Energy consumption of a non-coordinator device in } G_i \]

\[ E_i = \sum_{j \neq c} E^j_{i} + \left[ \frac{S}{(R_{t2}(M^c_i, BS))} \right] \cdot P \cdot N_i \quad \rightarrow \quad \text{Total energy consumption in } G_i \]

\[ R_{t1}(M^c_i, M^j_i) = B_{t1} \cdot \log_2 \left[ 1 + \left( P \cdot \left( h_{t1}(M^c_i, M^j_i) \right)^2 \right)/\left( N_0 \cdot B_{t1} \right) \right] \quad \rightarrow \quad \text{Achievable bitrate in } \ell_1\text{-type links} \]

\[ R_{t1}(M^c_i, BS) = B_{t2} \cdot \log_2 \left[ 1 + \left( P \cdot \left( h_{t2}(M^c_i, BS) \right)^2 \right)/\left( N_0 \cdot B_{t2} \right) \right] \quad \rightarrow \quad \text{Achievable bitrate in } \ell_2\text{-type links} \]

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Grouping and coordinator-based solutions (Cont ‘d)

– Split the problem into two sub-problems
  • Subproblem-1: Group the M2M devices
  • Subproblem-2: Assign coordinator to each group

Group M2M devices (K-Means)

Assign coordinator to each group (Initially randomly selected)

Iterate until total energy converges to a minimum

Tu et al., “Energy-efficient algorithms and evaluations for massive access management in cellular based machine to machine communications,” VTC-Fall, Sep. 2011
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At each iteration:

• Given centroids of each group
• Group selection criteria for a non-coordinator M2M device:

\[ M_k^j \in G_k \mid h_{\ell_1}(M_k^j, M_k^c) \leq h_{\ell_1}(M_k^j, M_m^c), \quad \forall m \]

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Using the M2M device groups, select new coordinators for each group
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Run K-Means to cluster the non-coordinator M2M devices according to the centroids.

The iteration stops when total energy consumption converges to a global minimum.

\[ M^j_k \in G_k | h_{\ell_1}(M^j_k, M^c_k) \leq h_{\ell_1}(M^j_k, M^c_m), \quad \forall m \]

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- Grouping and coordinator-based solutions

- Subproblem-2: Assigning coordinator to each group

  - Arithmetic means of channel gains (AM-CG)
    \[ M_k^c = \arg \max_{M_k^i} \left\{ \left(1/(n-1) \right) \cdot \sum_{j \neq i} h_{\ell_1}(M_k^i, M_k^j) \right\}, \ \forall k \]

  - Geometric means of channel gains (GM-CG)
    \[ M_k^c = \arg \max_{M_k^i} \left\{ \frac{1}{\sqrt[n-1]{\prod_{j \neq i} h_{\ell_1}(M_k^i, M_k^j)}} \right\}, \ \forall k \]

  - Select M2M device with max. channel gain in the link to the BS

  - Modified arithmetic means of channel gain (MAM-CG)
    \[ M_k^c = \arg \max_{M_k^i} \left\{ \left(1/(n-1) \right) \cdot \sum_{j \neq i} h_{\ell_1}(M_k^i, M_k^j) + \omega \cdot h_{\ell_2}(M_k^c, BS) \right\}, \ \forall k \]

  - Modified geometric means of channel gain
    \[ M_k^c = \arg \max_{M_k^i} \left\{ \frac{1}{\sqrt[n-1]{\prod_{j \neq i} h_{\ell_1}(M_k^i, M_k^j) + \omega \cdot h_{\ell_2}(M_k^c, BS)}} \right\}, \ \forall k \]

- Optimum energy consumption (OEC)

- K-maximal channel gains (KMAX-CG)

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Significant energy savings can be achieved (up to 25%)
Energy-efficient massive access control

Energy-efficient Power & Resource Allocation
- Group M2M devices and assign coordinators.
- Calculate initial values of Energy per bit (Epbd)

\[
Epbd_j = \frac{r_j^c}{(P_j^c + P_{\text{circuit}})} = \frac{\log_2(1 + P_j^c \cdot |h_{\ell_2}(M_j^c, BS)|^2 / N_0 / B_{\ell_2})}{P_j^c + P_{\text{circuit}}}
\]

Energy per bit

\[
P_j^c^{*} = 1/(Epbd_j \cdot \ln 2) - \left( N_0 \cdot B_{\ell_2} \right) / |h_{\ell_2}(M_j^c, BS)|^2
\]

Optimal transmitting power in an OFDMA frame

Energy-efficient massive access control

Energy-efficient Power & Resource Allocation
– Assign subcarrier for each coordinator
  • Assumption: Coordinators have different channel gains on different subcarriers
– In each iteration, for each unassigned subcarrier-coordinator tuple, calculate the following parameters:

\[ p_{jn}^* = \max\left( \left( B_c \cdot E \log_2(b_j(t - 1)) / \ln 2 - \left( N_0 \cdot B_c \right) / h_{\ell_2,n}(M_j^c, BS, t) \right)^2, 0 \right) \quad \text{Optimal transmission power} \]

\[ r_{jn}^* = \max\left( B_c \cdot \log_2 \left( [E \log_2(b_j(t - 1)) \cdot h_{\ell_2,n}(M_j^c, BS, t)]^2 / [N_0 \cdot \ln 2] \right), 0 \right) \quad \text{Optimal achievable bitrate} \]

Energy-efficient massive access control

Energy-efficient Power & Resource Allocation

How to assign subcarrier to a coordinator?

- For a subcarrier, select the coordinator leading to the minimum energy consumption

\[
I^n_{c_j} = \begin{cases} 
1 & M^n_j = \arg\min_{c_l \in C} \frac{D_{c_l} (p_{c_l}^n(t) + p_{cir})}{R_{c_l} (t-1)} \\
0 & \text{Otherwise}
\end{cases} \quad \forall n
\]

Overview:
- Target: M2M core
- Radio Access Network: OFDM
- WSN or AHN in the M2M device domain
- A centralized solution
- Suboptimal results when compared to the optimal solutions under frequency selective fading
- Optimal solutions are possible with exhaustive searching

START

- Cluster the M2M devices
- Select coordinator nodes
- Set initial values of \( E_{pb_j}^c \)

\( n: \) Subcarrier ID, \( n \leftarrow 1 \)

\( n > N \)

YES

- For each coordinator, \( M_j^c \) with \( D_j^c > 0 \):
  - Compute \( p_{jn}^c (t) \) and \( r_{jn}^c (t) \)
  - Assign subcarrier \( n \), and allocate power
  - Update total data for assigned coordinator, \( c \):
  - Update energy consumption of assigned coordinator
  - \( n \leftarrow n + 1 \)

NO

- Update \( P_j^c(t), R_j^c(t), f_j^c(t) \) for all coordinators

\( D_j^c > 0 \) for all \( c \)

\( t \leftarrow t + 1 \)

END
Energy-efficient relaying in M2M Networks

Overview:
- Target: M2M core / M2M Device Network
- Radio Access Network: IEEE 802.16p
- WSN or AHN in the M2M device domain
- A distributed solution
- Smart metering scenario
- Link quality improvement and energy savings

- L different types of meters
- Packet transmission duration: $T^{ON}_i$
- Duration between two packet transmissions is uniformly distributed
- Edge M2M devices experience self-similar packet arrival
- Relay experiences Poisson packet arrival
- Relay can eavesdrop the transmission channel at the aggregation point
- Relay can store a single packet for possible retransmission to the BS

Energy-efficient reporting

Overview:
• Target: M2M Device Domain
• Radio Access Network: Not considered
• WSN in the M2M device domain
• Centralized and/or distributed solutions
• Objective: Reporting VALID data with minimum energy

Formal expression of a valid data:
\[ \theta_m: \text{Monitoring period (MP) for the sensed data of type-} \text{-m} \]

\[ t + (i - 1) \cdot \theta_m \leq t_x < t'_x \leq t + i \cdot \theta_m \]

Energy-efficient reporting

- **M2M Gateway:**
  - Obtain a transmission schedule for the M2M devices
  - Ensure maximum energy savings
  - Ensure maximum valid data delivery

Value of MP durations:
\[
\Theta_m = \alpha_m \cdot \Theta_1, \quad \forall m \in \{1, ..., \mathcal{K}\}
\]

Gateway defines a cycle with length:
\[
L_c = \text{lcm}(\alpha_1, ..., \alpha_\mathcal{K}) \cdot \Theta_1
\]

X: A 3D-array with binary elements
\[
X_{[m][n][k]} = 1 \text{ if node-k is scheduled to transmit its sensed data of type-m in the transmission unit } n \text{ within the next cycle}
\]

Energy-efficient reporting

- **M2M Device-i:**
  - Sensing set $S_i$.

- **M2M gateway:**
  - Uses the union of the sensing sets $\tilde{S} = \{S_1, \ldots, S_i, \ldots, S_M\}$
  - Find a subset of $\tilde{S}$ s.t. Cover the complete sensing set, $S$.
  - Run a greedy algorithm
    - Energy-efficient Centralized Reporting (ECR)

Energy-efficient reporting

Energy-efficient reporting

- **M2M gateway:**
  - Broadcast the transmission schedule, $X$

- **M2M device receiving $X$:**
  - Stays in the active mode
  - Calculates its sensing set for each transmission unit in the next cycle
  - For the transmission units, $X[m][n][k]=0$, M2M device-k stays in the sleep mode
  - At the end of the cycle, wakes up to listen for the broadcast of $X$.

Sleep scheduling in M2M networks

- Existing power saving solutions in 3GPP
  - In Access Stratum (AS)
    - Longer paging cycles to avoid frequent monitoring of the paging channels
  - In Non-Access Stratum (NAS)
    - Longer timer helps avoiding frequent Location Area Updates (LAU) and Routing Area Updates (RAU)
- How to reduce power consumption in M2M device activities, network operations and signalling?

Sleep scheduling in M2M networks

- An extended idle mode for low-mobility devices

Sleep scheduling in M2M networks

- A new paging mechanism is proposed
  - Existing paging schemes cannot distinguish M2M devices and H2H devices in a paging occasion

- Three layers
  - Paging occasion
    - Use M2M group IDs
  - Paging target
    - If individual or group ID cannot be found, paging mechanism stops for the M2M device
  - Paging reason
    - Call setup request
    - M2M report
    - M2M system update

Energy-Efficiency and Security in M2M Networks...

- Energy-efficiency and security in M2M networks
  - Most components in the M2M device domain are unattended
    - Vulnerability
  - The ease of eavesdropping in wireless medium
  - Heterogeneous nature of the M2M device domain
    - some nodes may not participate asymmetric cryptographic operations due to their power and resource limitation

Three types of nodes:
- **Type-1**: Unable to support PKC operations
- **Type-2**: Plain text encryption, signature verification
- **Type-3**: High energy, advanced computing power and storage facility

A sensor node of Type-1

B: remote server

A wants to establish a session key with B

A selects the proxy nodes to perform PKC operations

The proxy nodes establish secured connections with B.

A prepares the shared secret, splits it among the proxy nodes

The proxy nodes transmit the shared secret to B in a secure way

B validates the messages received through multiple proxy nodes, assembles the validated messages to recover the master key

A and B verify B has received the same master key with A

B provides the list of proxy nodes participated in PKC operations so that A can exclude the non-participating nodes in the next round
Summary & Conclusion

- Energy-efficiency is a key challenge in M2M networks as M2M devices run on limited battery power

- Solutions covered
  - Massive access control
  - Power & Resource Allocation
  - Cooperative communications
  - Energy-efficient reporting
  - Sleep scheduling
  - Energy-efficient security

- Open issues
  - QoS provisioning
  - Novel security schemes in healthcare, metering and smart grid services
  - Energy saving protocols in the M2M core
What we have not covered...

- Energy-efficient routing in M2M networks. Basically;
  - Energy-efficient routing in WSNs
  - Energy-efficient routing in AHNs

- Energy harvesting for M2M devices.
  - Can be covered by the smart grid research

- Energy-efficiency in the context of “green communications”
  - Energy source-awareness in M2M core is a possible future direction
In press....