Feedback-based Congestion Control Gateway Router in Home M2M Network

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1.0 Introduction

- M2M is stand for Machine to Machine.
- Ability of machines, assets and devices to exchange data with people or company’s management systems.
- Key technology in a wide-scale monitoring and control infrastructure, particularly the home network.
- Home security sensing, lighting control, HVAC systems, medical devices, entertainment system and etc.
- Allow machines to exchange information and actions without human guidance.

1.0 Introduction (cont.)

- A heterogeneous network that has a backbone network and multiple sub-network.
- There is a central machine Home Gateway (GW), managing the whole network and connecting the home network to the outside world.
- Home GW in charge of access control, QoS management, security management, and multimedia conversion.

Fig.1 Home M2M network architecture
1.0 Introduction (cont.)

- In this study, a **gateway router** is introduced.
- Gateway router is defined as a node that has both router function and gateway function to communicate with other nodes.
- Example, WLAN node that is embedded with IEEE802.15.4 protocol can communicate with ZigBee node.

2.0 Research Problem and Motivation

- **Problem:**
  
  The different traffic patterns and simultaneous data transmission can cause an extreme amount of traffic load on individual nodes of networks.

- **Motivation:**

  Congestion control (CC) is essential in home M2M network to maintain the good performance and QoS in the network.

  In this study, a **feedback based gateway router** to smartly control the congestion in home M2M network is introduced.
3.0 Related Work

- Julien Chaumond has used the packet’s trip times to detect congestion. The characteristics and distribution of One-way Trip Time, OTT were analyzed, then a scheme of detection based on OTT measurements was developed with validated by simulation over different circumstances.

- Ivan et al. used the statistical detection theory to develop detection mechanisms that can further enhance current Active Queue Management, AQM methods.

3.1 OTT based CC

- OTT is the time required for a packet to travel from a specific source to a specific destination.

\[
\text{OTT} = \sum_{j=1}^{n+1} D_j + \sum_{i=1}^{n} B_i + \sum_{i=1}^{n} (P_i)
\]

- Assumption:
  - Multiple-hop model with n hops.
  - Each hop is a FIFO queue with infinite buffer
  - Physical route does not change in the middle connection
  - Processing time is linearly dependence on the packet’s size
3.1 OTT based CC (cont.)

- The mean, $E(OTT)$ and variance, $Var(OTT)$ is used
- M/D/1 model
- The equation of sum buffering time is developed.
  \[ E(\sum_{i=1}^{n} B_i) = E|P| \cdot \sum_{i=1}^{n} \left( \frac{1}{\mu_i} \frac{\rho_i}{1 - \rho_i} (1 - \frac{\rho_i}{2} (1 - C_s^2)) \right) \]
  where $\mu_i$ is $i$th link’s bandwidth, $\rho_i$ is load factor of hop $i$ and $C_s^2$ is the service time variation coefficient
- Then the profile function to quantify the congestion on a network path is determined,
  \[ f^{-1}(x) = \frac{-x - 1 + \sqrt{2(C_s^2 - 1)x + x^2 + 2x + 1}}{C_s^2 - 1} \]
- Flaws of this scheme is congestion detection algorithm need to wait some time before actually increasing or decreasing the sending rate.

3.2 Queue Occupancy Distribution

- General equation:
  Gaussian approximation of the sum of TCP congestion windows
  \[ Q_i(k) = W_i(k) - \overline{RTT_i} \times C_i - \epsilon_i \]
  where $Q_i$ = number of packet of $i$th flow in the queue at time $k$
  $W_i$ = congestion window
  $\overline{RTT_i} \times C_i$ = number of packets currently in the link
  $\epsilon_i$ = number of packets dropped

  The router’s queue occupancy equation
  \[ Q(t) = \sum_i Q(t) = \sum_i W_i(t) - c \sum_i \frac{1}{\sqrt{\delta_i}} - \sum_i \epsilon_i \]
  where $c$ = proportional constant that relates the throughput and delay to the average marking probability $\delta$
3.2 Queue Occupancy Distribution (cont.)

- With gamma distribution, the probability density function

\[ P\{Q = q; \bar{q}, \theta\} = \frac{\bar{q}^{q-1}e^{-\bar{q}}}{\theta^q\Gamma(q)} \]

for \( q > 0 \), where \( \bar{q} \) is the mean of the Gamma distribution random variable \( Q \), \( \theta \) is the scale parameter and \( \Gamma \) is the Gamma function. Using this notation, \( E|Q| = \bar{q} \) and \( \text{Var}|Q| = \bar{q}\theta \)

- The parameters of resulting Gamma distribution are \( \bar{q} \) and \( \theta \):

\[ \theta = \frac{\gamma}{c_i^{\sqrt{\delta}} \left( c_1 - \sqrt{\delta} \right) \left( c_1 + \sqrt{\delta} \right)} \]

4.0 Research model

- Consider the home M2M network as showed Fig. 2.
- Two different type of network topologies are deployed; WLAN and ZigBee.
- When the amount of traffic increase as the sensing time decreases, the traffic load of ZigBee nodes around the cognitive gateway becomes significantly heavy.
- The overall network performance can be degraded rapidly due to the congested link towards the cognitive gateway.
4.1 Model Flow

- Assume ZigBee node has a scheme for hop-by-hop congestion detection.
- If the ZigBee node is going to be congested according to the queue length identification, then the preceding node will determine others possible route.
- Spatial Capacity (SC) is an indicator of “data intensity” in a transmission medium.
- SC around the ZigBee node is measured to distinguish the potential relay node in the relay region.

\[ SC = \frac{\text{maximum data rate [kbps]}}{\text{Transmission area [m}^2]} \]

**Table 1. SC in different Standard Protocol**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Max. Rate (Mbps)</th>
<th>Trans. Dist. (m)</th>
<th>Spatial Capacity (kbps/m)</th>
<th>Spatial Capacity (mbps/m²)</th>
<th>Spatial Capacity (kbps/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.15.3 (UWB)</td>
<td>110</td>
<td>10</td>
<td>11000</td>
<td>350.20</td>
<td>26.60</td>
</tr>
<tr>
<td>802.11a (WLAN)</td>
<td>54</td>
<td>35</td>
<td>1543</td>
<td>14.00</td>
<td>0.30</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>3.20</td>
<td>0.24</td>
</tr>
<tr>
<td>802.15.4 (ZigBee)</td>
<td>0.25</td>
<td>2</td>
<td>125</td>
<td>19.90</td>
<td>7.46</td>
</tr>
</tbody>
</table>

- Total SC in region R
  \[ TSC = \sum SC_{R,B} \]

![Fig. 3 ZigBee Congestion Control Flow Chart](image)

![Fig. 4 SC in two different Protocol](image)
4.1 Model Flow (cont.)

- The probability that a sender is able to take advantage of a relay is computed,

\[ P(N, D) = \int_{r=1}^{D} \frac{2r}{D^2} P_{k \geq 1}(r)dr \]

where \( N \) = node, \( D \) = any relay region that contained with the transmission region, \( r \) = distance between a sender and a receive, which the sender is able to communicate with the receiver using the higher data rate via a single relay,

\[ P_{k \geq 1}(r) = 1 - \left( 1 - \frac{\text{relay region}}{\pi D^2} \right)^{N-1} \]

; probability for some sender, at least one of the other \( N-1 \) node is in its relay region

- The nodes that within the region with high SC and \( P(N,D) \) will be to the high potential router.

- A broadcast message upon requesting for delivering its traffic load will send to the potential router nodes.

5.0 Model Flow (cont.)

- Gateway router consists of its own congestion detection and control mechanism

- Feedback-based control

- As long as the gateway router is not congested, it will forward the requested traffic load from ZigBee node.
6.0 Proposed Feedback-based Control

- Divide into two parts:
  1. Time-based control
  2. Queue length control
- Time-based control uses the distribution of OTT measurements to detect the congestion.
- Queue-based control uses a packet marking probability method to maintain the average queue occupancy around the desired queue.

![Fig. 6 Feedback based control for a gateway router](image)

6.1 Comparison Between Julian and Proposed Scheme

- Julian Scheme

**Equation 1:**
\[ QTT = \sum_{j=1}^{n+1} D_j + \alpha(P) + \sum_{i=1}^{n} B_i \]
where \( D_j \) is the physical transmission delay along the \( j \)th link, \( B_i \) is the buffering time at the \( i \)th router, \( \alpha(P) \) processing time at the routers

**Equation 2:**
By M/D/1 and M/GI/1 model
\[ E\left( \sum_{i=1}^{n} B_i \right) = E[P] \sum_{i=1}^{n} \frac{\rho_i}{\mu_i} \left( 1 - \rho_i \right) \left( 1 - C_s^2 \right) \]
where \( E(\sum_{i=1}^{n} B_i) \) is the mean of total buffering time, \( \mu_i \) is \( i \)th link’s bandwidth, \( \rho_i \) is charge rate of hop \( i \) and \( C_s^2 \) is the service time variation coefficient

Estimation of the global charge rate

**Equation 3:**
For each packet receive, need to estimate of its total buffering time,
\[ \beta_{t+1} = \beta_t - \bar{\alpha} |P_t| \]
where \( \bar{\alpha} = \frac{\text{cov}(\alpha, P)}{\text{var}(P)} \), \( \beta_t = \beta - \bar{\alpha} \bar{\rho} \)

**Equation 4:**
From (3), the mean buffering time \( \tilde{\beta}_t \) using an exponential averaging,
\[ \tilde{\beta}_{t+1} = \lambda \tilde{\beta}_t + (1 - \lambda) \bar{\beta}_t \]

**Equation 5:**
Define a function \( f \):
\[ f: \rho \rightarrow \frac{\rho_i}{1 - \rho_i} \left( 1 + \frac{\rho_i}{2} (C_s^2 - 1) \right) \]
6.1 Comparison Between Julian and Proposed Scheme (cont.)

Thus,
\[ \bar{B}_t \equiv E |P| \cdot \sum_{i=1}^{n} \left( \frac{1}{\mu_i} \cdot f(\rho_i) \right) \]
where \( \rho_i \) is the charge rate of the \( i \)th hop.
Define the global charge rate \( \bar{\rho} \) as
\[ \bar{B}_t \equiv E |P| \cdot \bar{\alpha} \cdot f(\bar{\rho}) \]
\( f: [0,1] \rightarrow [0, +\infty] \)

Equation 6:
\[ \bar{\rho}_t = f^{-1} \left( \frac{\bar{B}_t}{E|P| \cdot \bar{\alpha}} \right) \]
For explicit expression of \( f^{-1} \)
\[ f^{-1}(x) = \frac{-x - 1 + \sqrt{2(C_x^2 - 1)x + x^2 + 2x + 1}}{C_x^2 - 1} \]

Proposed Scheme:
- Equation 1 and 2 is same with Julian scheme, since there are general equations.
- Equation 2 has been proven near to the reality network situation, except the arrivals at the queue with poison process (experiment).
- Equation 3,
\[ \bar{B}_t = \alpha \cdot \bar{T} - \bar{T} - \bar{\alpha} |P|_t \]
where \( \bar{T} = \alpha \cdot \bar{T}(t) - \bar{T}(t - 1) \), \( \bar{\alpha} = \left( \sum_{j=1}^{n \uparrow} \frac{1}{\mu_j} \right) \)
- Equation 4 is a general equation, thus will be remained as same.
\[ B_{t+1} = \lambda \cdot \bar{B}_t + (1 - \lambda) \cdot \bar{B}_t \]
- Equation 5:
\[ \bar{\rho}_t - \bar{\rho}_{t-1} = f^{-1} \left( \frac{\bar{B}_t - \bar{B}_{t-1}}{E|P| \cdot \bar{\alpha}} \right) \]
\( f: [0,1] \rightarrow [0, +\infty] \) need to be proved
- Equation 6:
\[ \bar{\rho}_t - \bar{\rho}_{t-1} = f^{-1} \left( \frac{\bar{B}_t - \bar{B}_{t-1}}{E|P| \cdot \bar{\alpha}} \right) \]
For explicit expression of \( f^{-1} \)
\[ f^{-1}(x) = \frac{-x - 1 + \sqrt{2(C_x^2 - 1)x + x^2 + 2x + 1}}{C_x^2 - 1} \]
- \( \bar{\rho}_t \) range must be within 0 to 1
6.2 Comparison Between Ivan and Proposed Scheme

Equation 1:
Gaussian approximation of the sum of TCP congestion windows
\[ Q_i(k) = W_i(k) - \frac{RTT_i}{c_i} \times C_i - \epsilon_i \]

where \( Q_i \) is the number of packets of the \( i \)th flow in the queue at time \( k \), \( W_i \) is the congestion window, \( RTT_i \times C_i \) is the number of packets currently in the links, and \( \epsilon_i \) is the number of packet dropped.

Used the relationship
\[ RTT_i \times C_i = \frac{c}{\sqrt{\delta}} \]

where \( c \) is proportionality constant that relates the throughput and delay to the average marking probability \( \delta \).

Equation 2:
The distribution of router's queue occupancy,
\[ Q(t) = \sum_{i} Q_i(t) = \sum_{i} W_i(t) - c \sum_{i} \frac{1}{\sqrt{\delta}} - \sum_{i} \epsilon_i \]

Assume that each flow gets a similar marking probability \( \delta \).

Equation 3:
Gamma distribution is used to model the queue occupancy process
\[ P\{q_l \leq Q < q_h, \bar{q}; \theta\} = \int_{q_l}^{q_h} \frac{q^{\theta-1} e^{-q/\theta}}{\theta^\theta \Gamma(\theta)} dq \]

For \( q_h > q_l \geq 0 \) where \( \bar{q} \) is the mean of Gamma distributed random variable \( Q \), \( \theta \) is the scale parameter, and \( \Gamma \) is the Gamma function.

6.2 Comparison Between Ivan and Proposed Scheme (cont.)

Equation 4:
The parameters of the resulting Gamma distribution are \( \bar{q} \) and \( \theta \)
\[ \theta = \frac{\bar{q}}{c_1 \sqrt{\delta}} \left( \frac{c_1 - \sqrt{\delta}}{c_1 + \sqrt{\delta}} \right) \]

Equation 5:
Likelihood ratio test (LRT).
Define \( q_o \) as an observation of the router's queue occupancy level and \( \bar{q} \) the ergodic average of the queue. The probability the \( q = q_o \), for a given set of parameters \( \bar{q} \) and \( \theta \), is given by
\[ P\{Q = q_o; \bar{q}, \theta\} = \frac{\max_{q=q_o} \Lambda(q_o)}{\max_{q=\bar{q}} \Lambda(q_o)} \]

where \( \Lambda(q_o) \) is defined as the likelihood of congestion given an observation \( q_o \).

The function \( \Lambda \) takes values in \((0, \infty)\), values close to 0 indicate certainly of link underutilization, and values around 1 indicate about the degree of congestion.

Proposed Scheme:
- Active Queue Management (AQM) with the control function of Random Early detection (RED) is implemented.
- Two considers part:
  - Queue Function
  - Control Function
- Queue Function:
  Equation 1:
\[ Q_i(k) = W_i(k) - OTT_i(k) \times C_i - \epsilon_i \]
\[ \epsilon_i = 0, \text{ if the link is going to be congested, reject to transmit any packets.} \]
6.2 Comparison Between Ivan and Proposed Scheme

The router’s queue occupancy becomes

\[ Q(t) = \sum Q_i(t) = \sum W_i(t) - c \sum \frac{1}{\sqrt{\delta}} - 0 \]

Parameters of \( W_i \) and \( \frac{1}{\sqrt{\delta}} \) are investigating.

Equation 2:

Control Function follow the RED algorithm,

\[ p = H(\bar{q}) \]

\[ = \begin{cases} 
0, & 0 \leq \bar{q} < q_{min} \\
\frac{\bar{q} - q_{min}}{q_{max} - q_{min}}, & q_{min} \leq \bar{q} < q_{max} \\
1, & q_{max} \leq \bar{q} \leq B 
\end{cases} \]

B is the buffer size

7.0 Conclusion Remark

- Feedback based congestion control for gateway router is needed to mitigate the Home M2M network.
- However, there are still a lot open issues need to be clarified before proceed to the simulation.
- **Short term research:**
  1. Construct the feedback based congestion control in this two types of protocol in heterogeneous network and more different types of protocol will be included in the future.
  2. Develop the SC measurements and identify the potential router scheme.
- **Long term research:** Network Coding and Mobility router to obtain 100% of overhearing will be investigate to robust the above scheme and solve the congestion problem.
Thank you for your Attention and Suggestions