Performance Evaluation on 6LoWPAN and PANA in IEEE 802.15.4g Mesh Networks

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Abstract

In this paper, we evaluate performance of 6LoWPAN and PANA over a mesh network based on mathematical analysis, considering IEEE 802.15.4 MAC/PHY behavior, 6LoWPAN behavior including fragmentation and PANA protocol behavior. End-to-end IP packet error rate, mean end-to-end IP packet delay, PANA session failure rate and mean PANA session establishment delay are used as the performance criteria. We show tradeoff points between Long Frame and Short Frame profiles for 6LoWPAN and PANA performance. As a result of performance analysis, we show a recommended PANA profile for IEEE 802.15.4g mesh networks to use Long Frame profile as long as MAC performance metric meet certain criterion.

Keywords: IEEE 802.15.4, 6LoWPAN, PANA, Fragmentation, Performance evaluation.

1 Introduction

Wireless mesh networks continue to deploy throughout the Smart Grid especially for HAN (Home Area Network) and NAN (Neighborhood Area Network) where efficient network devices and efficient operations of the devices are needed. ZigBee IP [1] is a IPv6-based network stack profile over

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IEEE 802.15.4 [2] wireless mesh network for HAN. There is similar work underway to establish a profile for not only the HAN but for the NAN.

ZigBee IP uses PANA (Protocol for carrying Authentication for Network Access) [3] for network access authentication by transporting EAP (Extensible Authentication Protocol) [4], in conjunction with PANA relay extension [5] that is required for PANA to operate over multi-hop networks.

PANA is designed to be independent of link-layer technologies and is proven to be interoperable over small-scale ZigBee IP HANs that typically have only one or two hops between an end-device and the ZigBee IP coordinator. There has been no study on PANA for a large-scale IEEE 802.15.4 NAN. In order to define a NAN profile, it is important to clarify operational conditions of PANA for meta-networks that are common within the NAN.

The main goal of this document is to evaluate performance of 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) [6] and PANA over large-scale IEEE 802.15.4 mesh networks and define a PANA profile that works for NAN environments. In this paper, we develop a mathematical model for 6LoWPAN and PANA over a mesh network to evaluate the following performance metrics: end-to-end IP packet error rate and mean end-to-end IP packet delay, PANA session failure rate and mean PANA session establishment delay. Accuracy of the mathematical model for 6LoWPAN performance analysis is validated by simulation. We show tradeoff points between Long Frame and Short Frame profiles for 6LoWPAN and PANA performance.

Based on the performance evaluation, we show a recommended PANA profile GFSK (Gaussian Frequency-Shift Keying) PHY based IEEE 802.15.4g mesh networks to use Long Frame profile as long as MAC performance metric meet certain criterion. We further explore a cross-layer mechanism for dynamically changing fragment size taking into account not only the PHY and MAC profiles and performance metrics but also the application layer profiles and performance metric.

2 Network Model

The following network model is used. See also Figure 1. All nodes in the same IEEE 802.15.4g mesh network support IPv6 and 6LoWPAN for encapsulating IPv6 packets over 802.15.4 MAC. Each IEEE 802.15.4g MAC PDU (i.e., a MAC frame) can carry up to 2000 octets of MAC SDU. GFSK PHY with the maximum link speed of 100kbps is used where 1 symbol is equal to 1 bit. It is assumed that the channel is idle when an ACK frame is sent. A route-over mesh routing protocol such as RPL (IPv6 Routing Protocol for Low-Power

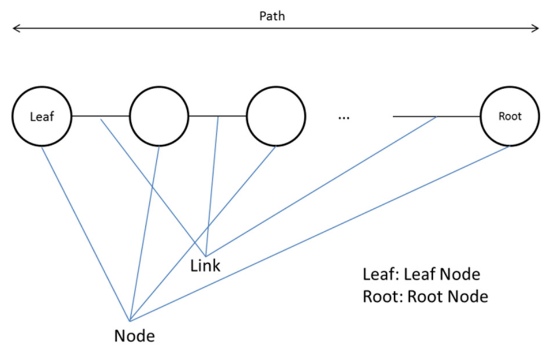

Figure 1 Network model

and Lossy Networks) [7] is used in the mesh network. The mesh network coordinator is referred to as a root node and the node on the other end of the PAN is referred to as a leaf node. The leaf node or the root node is the source node of 6LoWPAN packets. When the leaf node is the source node, the root node is the destination node, and vice versa. The path from the leaf node to the root node (i.e., the forward path) and the path from the root node to the leaf node (i.e., the reverse path) are symmetric. Hereafter the forward path and the reverse path are referred to as the path without distinction. There are H links along the path, constituting an H-hop path. 6LoWPAN header compression is not used. Fragmentation threshold for fragmenting an IP packet into multiple 6LoWPAN packets may be changed per packet and per hop, but does not change among multiple 6LoWPAN packets belonging to the same IP packet. The leaf node is the PaC and the root node is the PAA. For simplicity, we describe a model without utilizing the PANA relay element. On the other hand, our analysis can consider the impact of PANA relay by increasing the message size of each PANA message.

The following messaging model is used. See also Figure 2. The PaC initiates the PANA session. An authentication and authorization phase of a PANA session consists of an initiation followed by T transactions where T depends on the EAP authentication method in use. A successful initiation triggers the 1-st transaction. A successful i-th transaction triggers the (i+1)-st transaction. A PANA session is established if initiation and all T transactions are successful. An initiation consists of a PCI (PANA-Client-Initiation) message which is sent by the PaC. The PCI message will be retransmitted if the 1-st transaction does not start in a certain amount of time. The initiation is considered successful if the PCI message is received by the PAA before

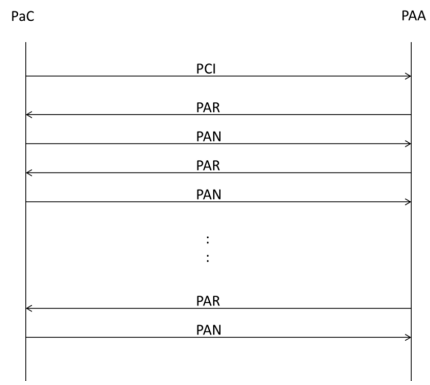

Figure 2 PANA messaging model

the number of retransmissions reaches its maximum value, *R*. A transaction consists of a PAR (PANA-Auth-Request) message sent by the PAA and a PAN (PANA-Auth-Answer) message sent by the PaC in response to the PAR. The PAR message will be retransmitted if the PAN message is not received in a certain amount of time. The transaction is considered successful if the PAN message is received by the PAA before the number of retransmissions reaches *R*. It is assumed that retransmissions of MAC frames of a PANA message in the network complete before the PANA retransmission timer for the PANA message expires.

3 Analysis

The notations used in the analytical model are shown in Table 1.

3.1 6LoWPAN Analysis

We analyze performance of IP over 6LoWPAN over an IEEE 802.15.4g mesh network employing un-slotted CSMA/CA with use of ACK frame (Figure 3). The sender of a data frame waits for LIFS (Long Inter-Frame Space) seconds after the last received ACK frame and before starting CSMA/CA back-off for data frame transmission. The sender of an ACK frame waits for SIFS (Short Inter-Frame Space) seconds after receipt of a data frame and before transmitting the ACK frame. The CSMA/CA back-off algorithm used in IEEE 802.15.4 MAC is shown in Figure 4.

1) End-to-end Packet Error Rate

First, $f_{l,tx}(L)$ is computed from f_b and $e_d(L)$ as $f_{l,tx}(L) = f_b+(1-f_b)\, e_d(L)$, where $f_b = 1 - \sum_{j=0}^{B_{\max}} c^j (1-c) = c^{B_{\max}+1}$.

Table 1 Notations

Name	Meaning
	MAC and PHY Parameters
L	Data frame size in octets.
L_a	ACK size in octets. $L_a = 4$ octets in IEEE 802.15.4.
M	Maximum number of retransmissions of link-layer frame.
$B_{\max}$	The maximum number of CSMA/CA back-offs (default = 4).
u	Back-off unit. $u = 20$ (bits) for GFSK PHY.
$E_{\min}$	Minimum back-off exponent (default = 3).
$E_{\max}$	Maximum back-off exponent (default = 5).
d_{AW}	ACK wait time. $d_{AW} = 6u/c$ for GFSK PHY..
d_{BO}	Mean CSMA/CA back-off time. $d_{BO} = (2^{E_{\min}} - 1)u/2/c = 70/c$.
d_{LIFS}	Inter-frame spacing latency for data. $d_{LIFS} = 40/c$ for GFSK PHY.
d_{SIFS}	Inter-frame spacing latency for ACK. $d_{SIFS} = 12/c$ for GFSK PHY.
d_{PROC}	Frame processing latency for data. We assume $d_{PROC} = 0.0$.
C	Link speed in bps. $C = 100000$ for GFSK PHY.
e	Bit error rate per link.
c	Channel busy rate.
	PANA Parameters
R	Maximum number of retransmissions of a PCI or PAR message.
T	Number of transactions. We use $T = 4$ which is a typical number for EAP-TLS.
m_0	The number of link-layer frames encapsulating a PCI message.
L_0	The frame length of each frame encapsulating a PCI message.
$m_{i,\mathrm{req}}$	The number of link-layer frames encapsulating a PAR message in i-th transaction.
$L_{i,\mathrm{req}}$	The frame length of each link-layer frame encapsulating a PAR message in i-th transaction.
$m_{i,\mathrm{ans}}$	The number of link-layer frames encapsulating a PAN message in i-th transaction.
$L_{i,\mathrm{ans}}$	The length of each link-layer frame encapsulating a PAN message in i-th transaction.
IRT_0	Initial retransmission interval in seconds for PCI message. We use $IRT_0 = 15$.
$IRT_{0,\max}$	Maximum retransmission interval in seconds for PCI message. We use $IRT_{0,\max} = 120$.
IRT_r	Initial retransmission interval in seconds for PAR message. We use IRT_r=10.
$IRT_{r,\max}$	Maximum retransmission interval in seconds for PAR message. We use $IRT_{r,\max} = 30$.

(Continued)

Table 1 Continued

	MAC Performance Metrics
$e_d(L)$	Frame error rate for data frame of length L octets. $e_d(L) = 8Le$.
e_a	Frame error rate for ACK frame. $e_a = 8L_a e$.
f_b	CSMA/CA failure rate for data frame.
$f_{l,tx}(L)$	Failure rate for transmission of a MAC data frame of length L octets.
$f_{l,tr}(L)$	Failure rate for an exchange of a MAC data frame of length L octets and an ACK frame sent in response to the data frame.
	6LoWPAN Performance Metrics
$f_p(m, L)$	Packet transmission failure rate over the path for an IP packet consisting of *m* 6LoWPAN frames of length L octets.
$d_l(m, L)$	Mean per-hop transmission latency in seconds for an IP packet consisting of m 6LoWPAN frames of length L octets.
$d_e(m, L)$	Mean end-to-end delay in seconds for an IP packet consisting of m 6LoWPAN fragments of length L octets.
	PANA Performance Metrics
${e_r}^{(i)}$	A failure rate of a PAR transmission in i-th transaction (i>0).
${e_t}^{(i)}$	A failure rate of *i*-th transaction.
e_S	A failure rate of PANA session establishment (i.e., PANA session error rate).
D	Mean PANA session establishment delay in seconds

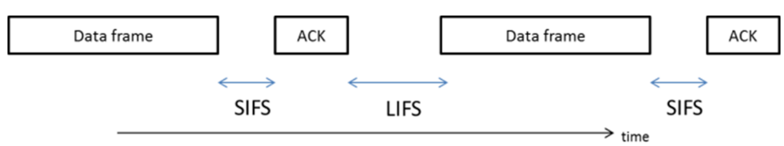

Figure 3 CSMA/CA with ACK

Based on the assumption that the channel is idle when ACK is sent, $f_{l,tr}(L)$ is calculated as $f_{l,tr}(L) = 1 - (1 - f_{l,tx}(L))(1 - e_a)$.

Since there are H links between the originating node and the destination node for an m–fragment IP packet, $f_p(m, L)$ is computed as $f_p(m,\ L) = 1 - \{(1 - f_{l,tr}(L)^{M+1})^{m-1}(1 - f_{l,tx}(L)^{M+1})\}^H$.

2) Mean End-to-end Packet Delay

Since the first $(m - 1)$ requires an ACK frame and the link-layer retransmission interval is $\mathrm{d_{AW}}$, the back-off time is $\mathrm{d_{BO}}$, and the MAC frame transmission latency is $8L/C$, and the transmission of an ACK frame for the last (i.e., m–th) data frame of an IP packet does not contribute to the latency

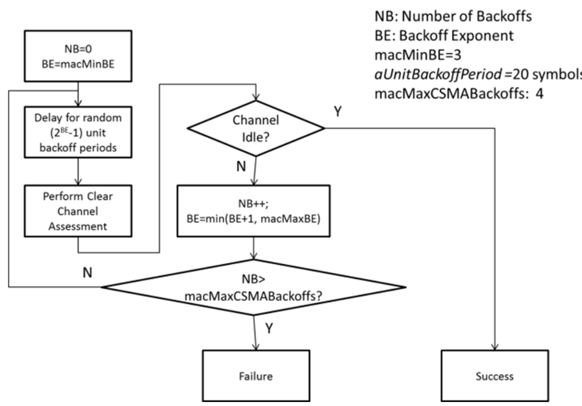

Figure 4 CSMA/CA Back-off Algorithm

of the IP packet for each hop, $d_l\,(m, L)$ is computed as follows.

$$d_l\,(m, L) = (\mathrm{m} - 1) \times$$

$$\frac{\sum_{j=0}^{M}\left(\begin{array}{c} j\,(8L/C{+}d_{BO}{+}d_{AW})+8\,(L{+}L_a)/C+ \\ d_{BO}{+}d_{LIFS}{+}d_{SIFS}{+}d_{PROC}\end{array}\right) f_{l,tr}\,(L)^j(1{-}f_{l,tr}(L))}{\left(1{-}f_{l,tr}(L)^{M+1}\right)^{m-1}} +$$

$$\frac{\sum_{j=0}^{M}(j(8L/C{+}d_{BO}{+}d_{AW}){+}8L/C{+}d_{BO}{+}d_{LIFS}{+}d_{PROC})f_{l,tx}(L)^j(1{-}f_{l,tx}(L))}{(1{-}f_{l,tx}(L)^{M+1})},$$

where

$d_{\mathrm{BO}} = \sum_{j=0}^{B_{\max}} (2^{\min(j+E_{\min},\, E_{\max})} - 1)\,(u/2C)\,c^j(1 - c)$

$d_e\,(m, L)$ is given by $d_e\,(m, L) = H d_l\,(m, L)$.

3.2 PANA Analysis

1) Session Failure Rate

Since a single transmission of a PAR message can result in a successful receipt of a PAN message when both the request and answer messages are successfully transmitted, ${e_r}^{(i)}$ is computed as:

$${e_r}^{(i)} = 1{-}\{1{-}f_p\,(m_{i,\mathrm{req}}, L_{i,\mathrm{req}})\}\{1 - f_p\,(m_{i,\mathrm{ans}}, L_{i,\mathrm{ans}})\}.$$

Since a transaction fails when all retransmissions of the PAR message fail, ${e_t}^{(i)} = \{{e_r}^{(i)}\}^{R+1}$.

Finally, a PANA session establishment fails when initiation fails or one of T transactions fails, e_s is computed as:

$$e_s = f_p(m_0, L_0)^{R+1} + \{1 - f_p(m_0, L_0)^{R+1}\}\{1 - \prod_{i=1}^{t}(1 - {e_t}^{(i)})\}.$$

2) Mean Session Establishment Delay

Let ${d_k}^{(i)}$ be the mean delay for i-th transaction that succeeds after k retransmissions. Then, for $i > 0$,

$${d_k}^{(i)} = g_k \min\left(IRT_r 2^{k-1}, IRT_{r,max}\right)$$
$$+H\left(d_e\left(m_{i,req}, L_{i,\mathrm{req}}\right) + d_e\left(m_{i,ans}, L_{i,\mathrm{ans}}\right)\right)$$, where

$$g_k = \begin{cases} 1, & k > 0 \\ 0, & k = 0 \end{cases} .$$

Let $d^{(i)}$ be the mean delay for i-th transaction, then $d^{(i)}$ is compute from ${d_k}^{(i)}$ as follows.

$$d^{(0)} = \frac{\sum_{k=0}^{R}\{g_k \min\left(IRT_0 2^{k-1},\ IRT_{0,\max}\right) + H d_e(m_0, L_0)\} f_p(m_0, L_0)^k (1 - f_p(m_0, L_0))}{1 - f_p(m_0,\ L_0)^{R+1}}.$$

$$d^{(i)} = \frac{\sum_{k=0}^{R} {d_k}^{(i)}\{{e_r}^{(i)}\}^k (1 - {e_r}^{(i)})}{1 - {e_t}^{(i)}}, i > 0.$$

Finally, $D = \sum_i^T d^{(i)}$

Note that the computed D value is valid if the maximum roundtrip time is smaller than the initial retransmission interval. Therefore, the operational condition of the system is given by:

$H < \frac{IRT_r C}{2m_{\max}(8L)}$, where $m_{\max} = \max\{\max_i\{m_{i,\mathrm{req}}\},\ \max_i\{m_{i,\mathrm{ans}}\}\}$.

For example, $H \le 28$ for $(m_{\max},\ L, IRT_r) = (17, 127, 10)$, and $H \le 47$ for $(m_{\max},\ L, IRT_r) = (1, 1327, 10)$.

4 Performance Evaluation

We use two types of fragment size profiles, i.e., "Short Frame" and "Long Frame" as described in Table 2.

Table 2 Fragment Size Profile

6LoWPAN Parameter	Value	
	Short Frame	Long Frame
Maximum fragment size	127 octets	1327 octets

4.1 6LoWPAN Evaluation

First, we show 6LoWPAN performance in terms of packet loss rate given by $f_p\,(m,\ L)$ and mean delay given by $d_e\,(m, L)$ for an IPv6 packet of length 1280 octets, $M=$ 3, and $H= 1, 2 \ldots 10$, where $(m, L) =$ (18, 127) for Short Frame profile and $(m, L) =$ (1,1327) for Long Frame profile . Results for 4 cases (c, e) $= (0.0,\ 0.00001)$, $(0.0,\ 0.00003)$, $(0.2,\ 0.00001)$, $(0.2,\ 0.00003)$ based on analysis and simulation are shown in Table 3, Table 4, Table 5, and Table 6, respectively. Tens of thousands of IP packets are generated in each simulation run. In the simulations, adjacent nodes are placed at a distance of 100m which is equal to the radio coverage. These tables indicate that difference in analysis and simulation results are close in the examined parameter range. Specifically, mean delay difference is within 5.2 % and packet loss difference is within 2 orders of magnitude for packet loss rate higher than 10^{-6} and within the 1 order of magnitude for packet loss rate higher than 10^{-4}. Hereafter our evaluation is based on analysis only.

Table 3 6LoWPAN Performance (c = 0.0, e = 0.00001, M = 3)

Mean Delay				
	Short (c = 0.0, e = 0.00001, M = 3)		Long (c = 0.0, e = 0.00001, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0.206555	0.212455	0.119791	0.12054
2	0.413213	0.424909	0.240037	0.24108
4	0.826231	0.849818	0.479471	0.48216
6	1.239213	1.274727	0.715689	0.72324
8	1.652637	1.699636	0.95945	0.96432
10	2.065444	2.124545	1.197706	1.2054
Packet Loss Rate				
	Short (c = 0.0, e = 0.00001, M = 3)		Long (c = 0.0, e = 0.00001, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0	2.15E-07	0.0012	0.00012894
2	0.0001	4.31E-07	0.0026	0.00025786
4	0	8.62E-07	0.0052	0.00051565
6	0.0001	1.29E-06	0.0075	0.00077337
8	0.0001	1.72E-06	0.0118	0.00103103
10	0.0001	2.15E-06	0.013	0.00128862

Table 4 6LoWPAN Performance (c = 0.0, e = 0.00003, M = 3)

Mean Delay				
	Short (c = 0.0, e = 0.00003, M = 3)		Long (c = 0.0, e = 0.00003, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0.21072	0.21719	0.148083	0.154046
2	0.421656	0.43438	0.292793	0.308092
4	0.842965	0.868761	0.5877	0.616185
6	1.265098	1.303141	0.884022	0.924277
8	1.685981	1.737521	1.173841	1.232369
10	2.107599	2.171902	1.46821	1.540462
Packet Loss Rate				
	Short (c = 0.0, e = 0.00003, M = 3)		Long (c = 0.0, e = 0.00003, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0.0004	1.7412E-05	0.0348	0.01044388
2	0.0007	3.4823E-05	0.0646	0.02077869
4	0.0015	6.9644E-05	0.1249	0.04112562
6	0.0031	0.00010446	0.1753	0.06104977
8	0.0028	0.00013928	0.2349	0.08055992
10	0.0035	0.0001741	0.2827	0.09966467

Table 5 6LoWPAN Performance (c=0.2, e = 0.00001, M = 3)

Mean Delay				
	Short (c = 0.2, e = 0.00001, M = 3)		Long (c = 0.2, e = 0.00001, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0.214697	0.216583	0.12002	0.120828
2	0.42972	0.433165	0.240763	0.241656
4	0.859242	0.86633	0.480075	0.483311
6	1.288571	1.299496	0.72124	0.724967
8	1.718689	1.751807	0.961933	0.966623
10	2.147817	2.189758	1.203159	1.208278
Packet Loss Rate				
	Short (c = 0.2, e = 0.00001, M = 3)		Long (c = 0.2, e = 0.00001, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0	2.4277E-07	0.0012	0.00013033
2	0	4.8553E-07	0.0019	0.00026064
4	0.0001	9.7106E-07	0.0045	0.0005212
6	0.0002	1.4566E-06	0.0073	0.0007817
8	0.0003	1.9421E-06	0.0119	0.00104213
10	0.0003	2.4277E-06	0.0154	0.0013025

Next we show packet loss rate and mean packet delay performance in broader set of parameters. Figure 5 and Figure 6 show packet loss rate versus H for $(c, e) = (0.1, 0.00001)$, $(0.1, 0.00003)$, respectively for $M = 3, 7$. Figure 7 and Figure 8 show mean packet delay versus H for

Table 6 6LoWPAN Performance (c = 0.2, e = 0.00003, M = 3)

	Mean Delay			
	Short (c = 0.2, e = 0.00003, M = 3)		Long (c = 0.2, e = 0.00003, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0.219133	0.221407	0.147527	0.154403
2	0.43853	0.442815	0.295205	0.308806
4	0.876995	0.88563	0.58945	0.617612
6	1.31556	1.328445	0.885841	0.926418
8	1.754518	1.77126	1.177391	1.235224
10	2.192648	2.214075	1.477293	1.544031
	Packet Loss Rate			
	Short (c = 0.2, e = 0.00003, M = 3)		Long (c = 0.2, e = 0.00003, M = 3)	
H	Simulation	Analysis	Simulation	Analysis
1	0.0006	1.811E-05	0.0351	0.01047236
2	0.0013	3.622E-05	0.0632	0.02083505
4	0.0022	7.2439E-05	0.1302	0.04123599
6	0.0029	0.00010866	0.1844	0.06121188
8	0.0058	0.00014487	0.2362	0.08077158
10	0.0061	0.00018109	0.2787	0.09992374

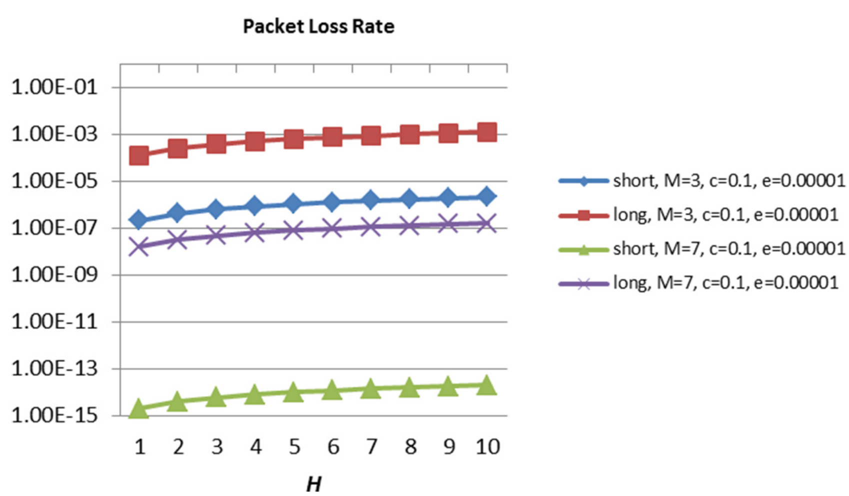

Figure 5 Packet Loss Rate vs. Number of Hops (c = 0.1, e = 0.00001)

$(c, e) = (0.1,\ 0.00001)$, $(0.1, 0.00003)$, respectively for $M = 7$. Note that mean packet delay values for $M = 3$ are nearly the same as those for $M = 7$. Short Frame shows more than 4 orders of magnitudes lower packet loss rate than Long Frame profile. On the other hand, Long Frame profile shows less than 1/2 the lower packet delay than Short Frame profile.

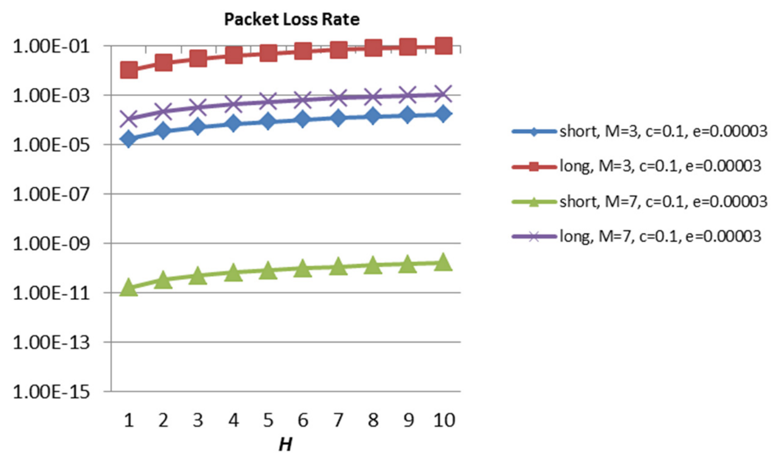

Figure 6 Packet Loss Rate vs. Number of Hops (c=0.1, e=0.00003)

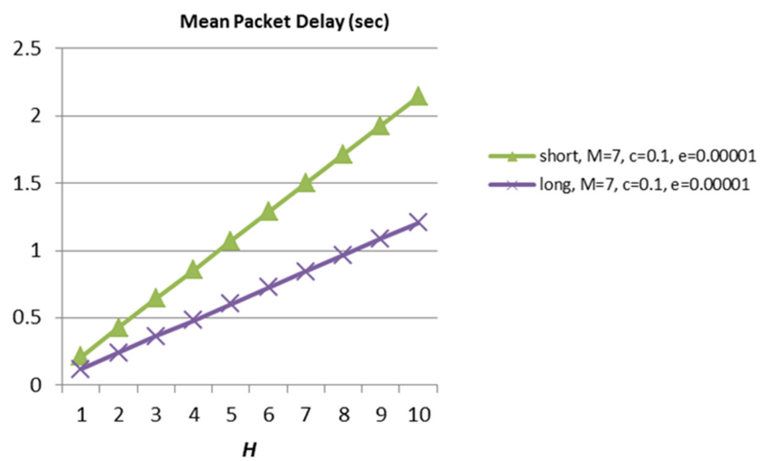

Figure 7 Mean Packet Delay vs. Number of Hops (c=0.1, e=0.00001)

Figure 9 and Figure 10 show packet loss rate and mean packet delay performance versus c, respectively, for $(H, e) = (10,\ 0.00001)$ and $M = 3, 7$. Again Long Frame profile shows less than ½ the lower packet delay than Short Frame profile. When channel busy rate is low, Short Frame profile shows smaller packet loss rate than Long Frame profile, but when channel busy rate exceeds a certain threshold, Short Frame profile incurs higher packet loss rate than Long Frame profile. This can be explained as follows. A MAC frame

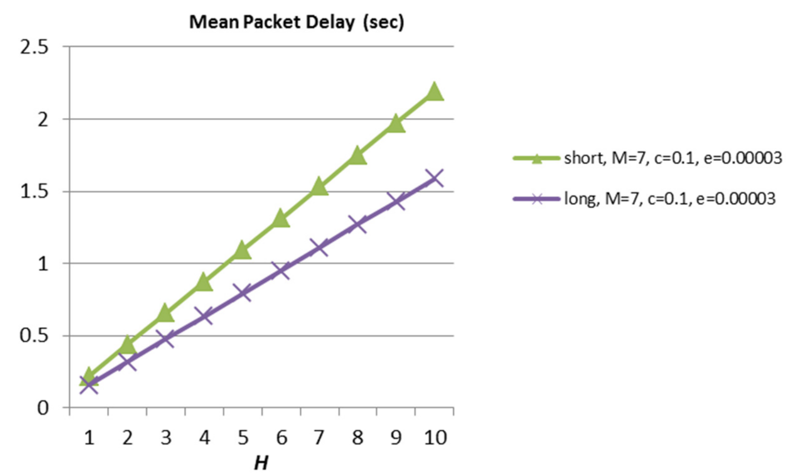

Figure 8 Mean Packet Delay vs. Number of Hops (*c*=0.1, *e*=0.00003)

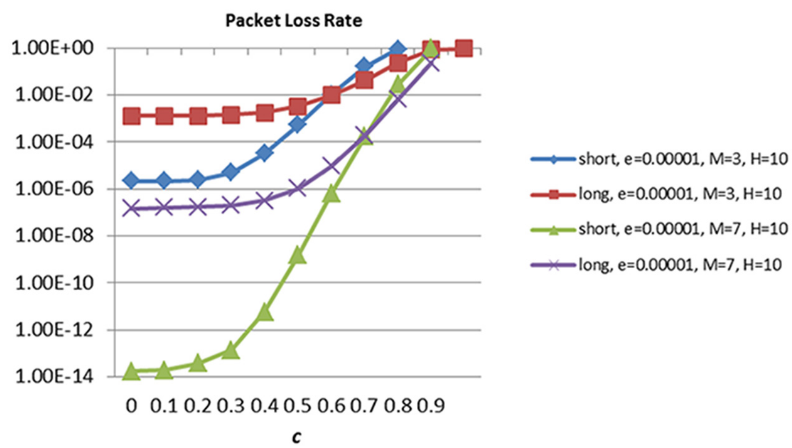

Figure 9 Packet Loss Rate vs. Channel Busy Rate

loss can be caused by bit errors and CSMA/CA back-off failures. The former occurs more frequently when the fragment size is large. On the other hand, the latter occurs more frequently when the channel busy rate is high. The benefit of smaller fragment size to be robust against bit errors is negated by the disadvantage of the larger number of smaller sized fragments which causes higher CSMA/CA back-off failure rate, and the disadvantage overwhelms the advantage where the channel busy rate exceeds the threshold.

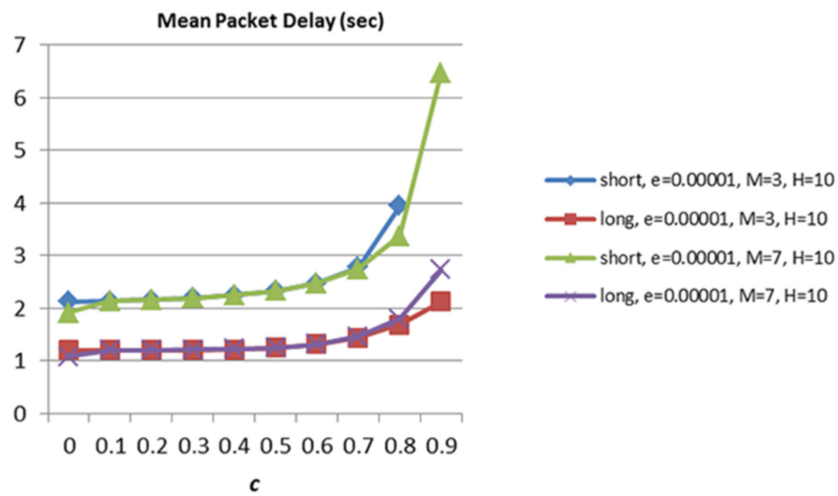

Figure 10 Packet Loss Rate vs. Channel Busy Rate

Table 7 PANA Profile

PANA Operational Parameters	Value	
	Short Frame	Long Frame
m_0	1 frame	1 frame
$m_{i,\text{req}}$, $m_{i,\text{ans}}$ $(0 < i \leq 4)$	16 frames	1 frame
L_0	127 octets	127 octets
$L_{i,\text{req}}$, $L_{i,\text{ans}}$ $(0 < i \leq 4)$	127 octets	1327 octets

4.2 PANA Evaluation

In this section we evaluate performance of PANA over 6LoWPAN in terms of packet loss rate given by e_S and mean session establishment delay given by D. We use the following profile for PANA. Both profiles are corresponding to PCI message of 80 octets in IP PDU length, followed by a sequence of T=4 pairs of PAR and PAN messages all of which have 1280 octets in IP PDU length.

Figure 11 and Figure 12 show PANA session failure rate versus M for $R = 1$ and $R = 5$, respectively for c $= 0.0$. Figure 13 and Figure 14 show PANA session establishment delay versus M for $R = 1$ and R= 5, respectively for c $= 0.0$. Figure 15 and Figure 16 show PANA session failure rate and PANA session establishment delay versus c , respectively, for H= 10, M= 7, and R= 5. The following observations can be made.

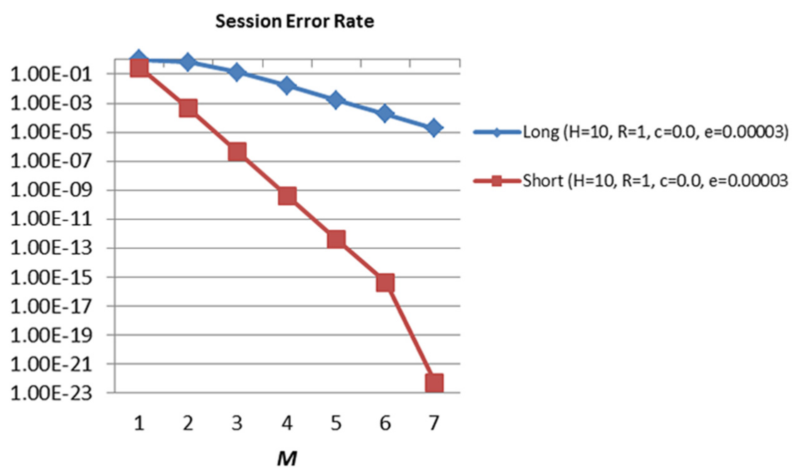

Figure 11 PANA Session Error Rate vs. Max. Number of MAC Frame Retransmission (*R*=1)

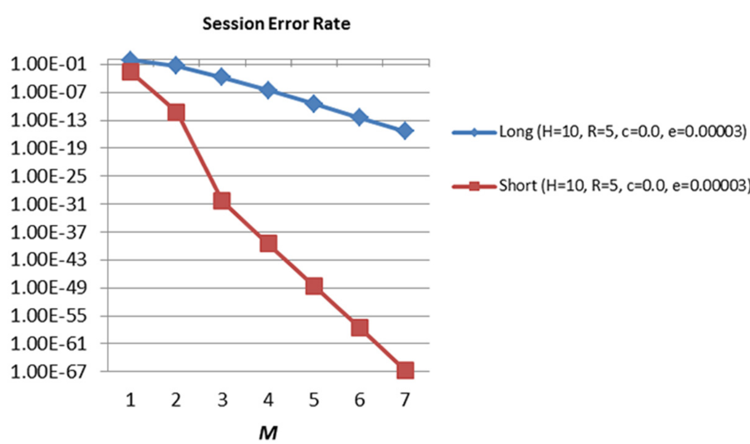

Figure 12 PANA Session Error Rate vs. Max. Number of MAC Frame Retransmissions (*R*=5)

Increasing the maximum number of MAC frame retransmissions can decrease both PANA session error rate and PANA session establishment delay for both Short Frame and Long Frame cases (Figure 11, Figure 12, Figure 13 and Figure 14). Increasing the maximum number of PANA message retransmissions can decrease PANA session error rate and increase PANA session establishment delay for both Short Frame and Long Frame cases (Figure 11, Figure 12, Figure 13 and Figure 14). Short Frame profile shows

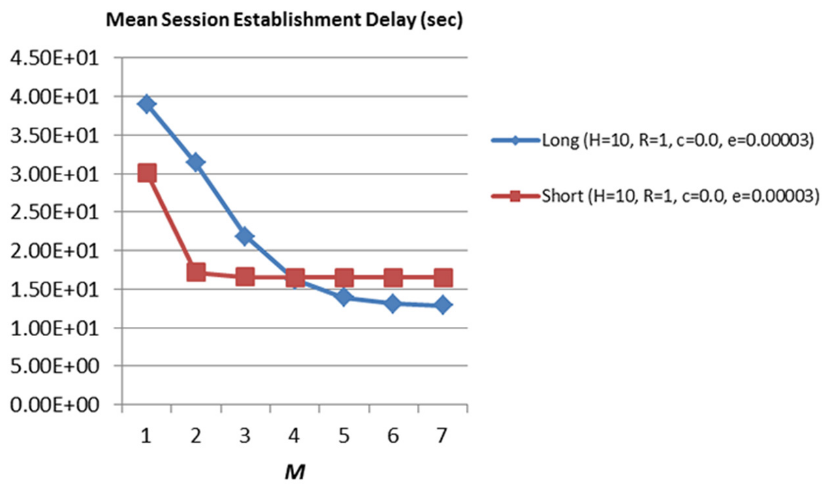

Figure 13 Mean PANA Session Establishment Delay vs. Max. Number of MAC Frame Retransmissions (*R*=1)

lower PANA session error rate than Long Frame profile when the channel busy rate is low (Figure 11 and Figure 12). Long Frame profile shows lower PANA session establishment delay than Short Frame profile when the maximum number of MAC frame retransmission is high (Figure 16). There is a threshold for the maximum number of MAC frame retransmissions below which PANA session establishment delay for Long Frame profile becomes larger than that for Short Frame profile when channel busy rate is low (Figure 13 and Figure 14). There is a threshold for the channel busy rate above which PANA session error rate for Short Frame profile becomes larger than that for Long Frame profile (Figure 15).

From these observations, it is recommended to use Long Frame profile defined in Section 0 for PANA with $M = 7$ and the following PANA session parameters for achieving PANA session error rate lower than 10^{-7} and mean PANA session establishment delay lower than 20 seconds in 6LoWPAN over IEEE 802.15.4g networks that employ GFSK PHY with the link speed (C) of 100 kbps with the number of hops (H) not exceding 10 and bit error rate (e) not exceeding 0.00003 and channel busy rate (c) not exceeding 0.6: $R = 5$, $IRT_0 = 15$, $IRT_{0,\max} = 120$, $IRT_r = 10$ and $IRT_{r,\max} = 30$

In the case where bit error rate on the outgoing link of a node exceeds 0.00003 and channel busy rate does not exceed 0.6, it is recommended to either switch to use Short Frame profile or use an alternative next hop node.

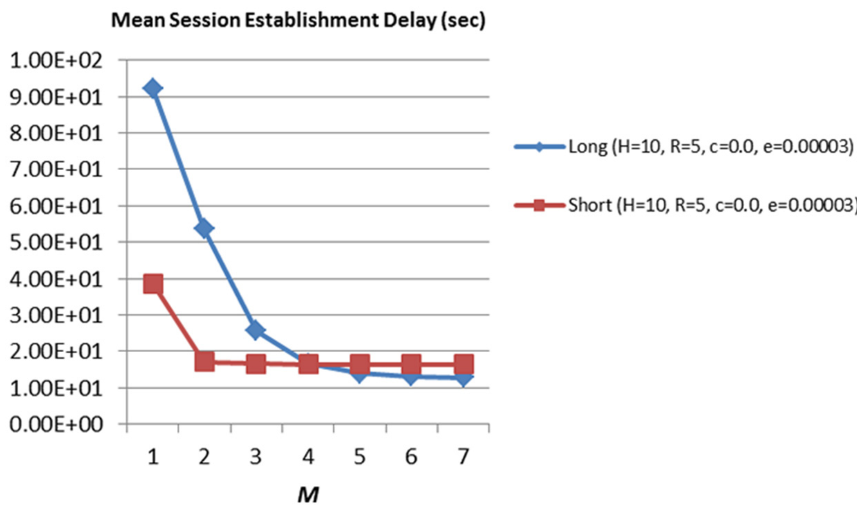

Figure 14 Mean PANA Session Establishment Delay vs. Max. Number of MAC Frame Retransmission (*R*=5)

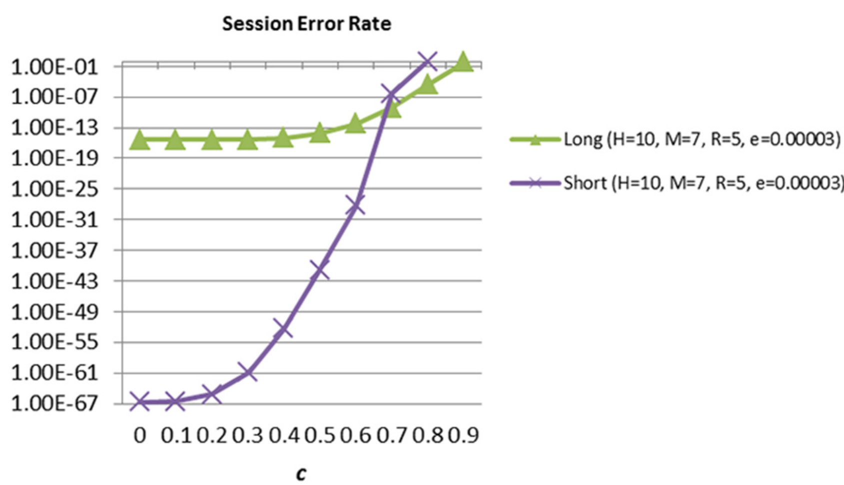

Figure 15 PANA Session Error Rate vs. Channel Busy Rate

In the case where channel busy rate on the outgoing link of a node exceeds 0.6, it is recommended to use an alternative next hop node without switching to Short Frame profile. A more simplified way is to use an alternative next hop node if packet loss rate bit error rate exceeds 0.00003 or channel busy rate exceeds 0.6.

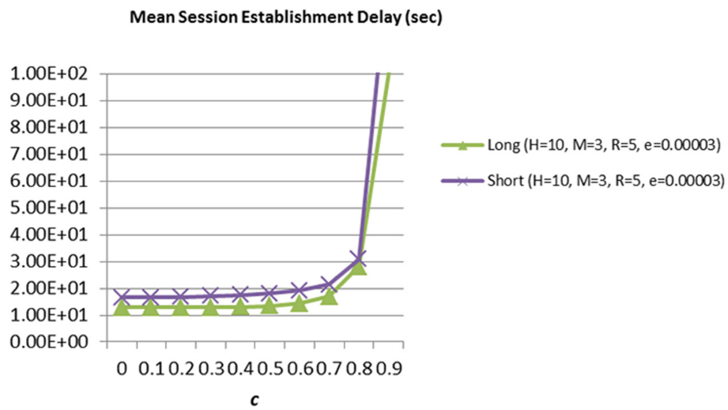

Figure 16 Mean PANA Session Establishment Delay vs. Channel Busy Rate

5 Guidelines on Fragment Size

Although the analysis and performance evaluation described in this paper is focused on PANA over IPv6 employing 6LoWPAN encapsulation, the obtained results lead to an insight into a cross-layer mechanism for dynamically changing fragment size taking not only the PHY and MAC profiles and performance metric but also application layer profiles and performance metric into accounts. As a rule of thumb, in the environments such as IEEE 802.15.4 wireless mesh networks where MAC frame loss rate is not ignorant, use of smaller 6LoWPAN fragment size is recommended for real-time applications since they do not rely on retransmissions above MAC layer, and use of larger 6LoWPAN size is recommended for non-real time applications that employs a transport or application layer retransmission mechanism that can compensate IP packet loss.

Note that this kind of dynamic fragment size control is applicable to IP-layer fragmentation as well. However, it is recommended to use 6LoWPAN fragmentation wherever available because 6LoWPAN provides not only fragmentation but also more efficient header compression schemes [8] than IP header compression [9].

6 Conclusions

In this document, we developed a mathematical model for 6LoWPAN and PANA over a mesh network to evaluate end-to-end IP packet error rate and mean end-to-end IP packet delay, PANA session failure rate and mean PANA session establishment delay.

Through performance evaluation of 6LoWPAN, we observed that Short Frame profile always shows larger mean packet delay than Long Frame profile, and when channel busy is low, Short Frame profile shows smaller packet loss rate than Long Frame profile. On the other hand, when channel busy rate exceeds a certain threshold, Short Frame profile incurs higher packet loss rate than Long Frame profile. Through performance evaluation of PANA over 6LoWPAN, we observed that increasing the maximum number of MAC frame retransmissions can decrease both PANA session error rate and PANA session establishment delay, and increasing the maximum number of PANA message retransmissions can decrease PANA session error rate at the cost of larger PANA session establishment delay. We also observed tradeoff points in terms of PANA session establishment delay as well as PANA session error rate between Long Frame and Short Frame profiles.

As a result, a recommended PANA profile was introduced for GFSK-based IEEE 802.15.4g mesh networks to use Long Frame profile as long as MAC performance metric meet certain criterion.

Finally, we explored an idea of cross-layer mechanism for dynamically changing fragment size taking not only the PHY and MAC profiles and performance metric but also application layer profiles and performance metric into accounts. We plan to investigate such a mechanism deeply in our future work.

7 Acknowledgment

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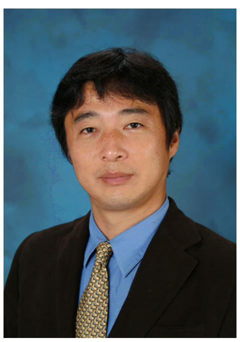

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