Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Performance evaluation of the Hybrid L2 Routing for IEEE 802.15.10

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Re:

Abstract: The performance evaluation for the IEEE 802.15 TG10 Recommended Practice to propose L2 Routing to be applied for IEEE 802.15.4 - especially cluster-Tree and TVWS multi-channel Tree PAN topologies.

Purpose: Response to the IEEE802.15 TG10 call for final proposal

Identification of the L2R Message (1/2)

- Data frame vs. Command frame structure
  - Only one (data) role vs. various roles (various command frames)
  - Utilized by all types of the devices vs. Utilized by special type of the device
  - Simplified structure vs. complex structure

Data frame format

Octets: 2	1	variable	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Data Payload	FCS
MHR				MAC Payload	MFR

Command frame format

Octets: 2	1	variable	0/5/6/10/14	1	variable	2
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Command Frame Identifier	Command Payload	FCS
MHR				MAC Payload		MFR

Identification of the L2R Message (2/2)

- L2R frame format
  - An L2R IE field is inserted to DATA payload.

Octet:2	1	variable	0/5/6/10/14	1	Variable	2
Frame Control	Sequence Number	Addressing Field	Auxiliary Security Header	L2R IE	L2R Header	FCS
MHR				MAC payload		MFR

- L2R Information Elements (IE)

L2R Information element	message type	RFD	
		Tx	Rx
0x01	PAN coordinator announcement		
0x02	PAN coordinator announcement reply		
0x03	P2P route request	X	X
0x04	P2P route reply	X	X
0x05-0xff	Reserved		

Hybrid L2R Frame Formats

- PANN,

Octet: Variable	1	8	1	1	1	4	4	1
MHR field (data or command)	L2R IE	Originator address of the frame initiator	Allocated channel number	HOP Count	TTL	PREQ sequence number	Metric	Request Status

- PANN-RP

Octet: Variable	1	8	8	1	2	Variable	8	1
MHR field	L2R IE	Originator address of the frame initiator	Originator address of the received PANN	Allocated channel number	Length	Associated PAN node Extended address	multicast address	PAN status

- PREQ

Octet: Variable	1	8	8	1	1	1	4	4	4	1
MHR field	L2R IE	Originator address of the frame initiator	Multicast address	Allocated channel number	HOP Count	TTL	PANN sequence number	Interval	Metric	Request Status

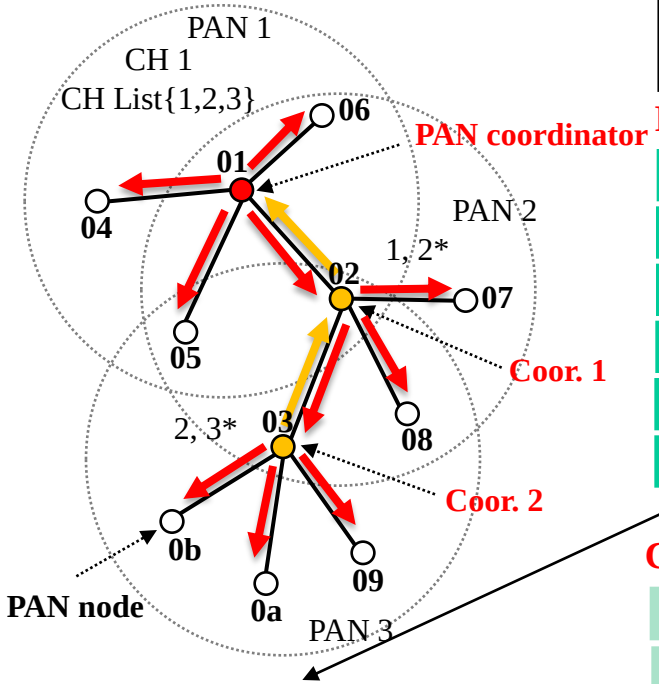
- PREQ-RP

Octet: Variable	1	8	8	1	1
MHR field	L2R IE	Originator address of the frame initiator	Originator address of the received PREQ	Allocated channel number	Reply Status

Multicast Routing in Hybrid L2R

- Initiated by PREQ
  - The node which has a multicast address transmits the PREQ with a multicast address.
  - Each node which receives the multicast PREQ inserts or updates the multicast routes.
- PREQ-RP with multicast response
  - Only a node which has an interest to the multicast address of received PREQ message responds to the multicast using PREQ-RP message.
  - The destination address of the PREQ-RP is set to the multicast address.
- Multicast relay device(s)
  - The node which receives the multicast address PREQ-RP sets the multicast status flag in routing table.
  - The Multicast frame is only rebroadcasted by multicast relay device(s) which receives PREQ-RP with multicast address.

An Example of Updating Routing Table



Octet:8	8	1	1	2	8	1	1
Dest./ Multicast Address	Associated PAN ID	HOP Count	L2R sequence number	Route expiration time	Extended Next hop Address	Next hop Allocated channel number	status
.							
.							
.							

PAN coordinator routing table

00:00:00:00:00:00:00:03	2	2	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:07	2	2	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:08	2	2	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:09	3	3	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:0a	3	3	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:0b	3	3	1	t	00:00:00:00:00:00:00:02	2	79

Coordnator 1 routing table

00:00:00:00:00:00:00:01	1	1	1	t	00:00:00:00:00:00:00:01	1	127
00:00:00:00:00:00:00:09	3	2	1	t	00:00:00:00:00:00:00:03	3	79
00:00:00:00:00:00:00:0a	3	2	1	t	00:00:00:00:00:00:00:03	3	79
00:00:00:00:00:00:00:0b	3	2	1	t	00:00:00:00:00:00:00:03	3	79

Coordinator 2 routing table

00:00:00:00:00:00:00:01	1	2	1	t	00:00:00:00:00:00:00:02	2	127

status bit mask	Description
0x01	Uplink direction
0x02	Downlink direction
0x04	Route established
0x08	Proactive route
0x10	Gateway enabled node (internet connection)
0x20	SPC enabled
0x40	TMCTP enabled (Multi-channel operation)
0x80	multicast route

Summary of the Hybrid L2R

- Unique characteristics
  - Support multi-channel routing
  - Support both IEEE 802.15.4 and TVWS Multi-Channel Tree Topology
- Frame identifier
  - Information Elements
- Support traffic pattern
  - M:1 (uplink: to the gateway)
  - 1:M (downlink: gateway or a device to the each device)
    - Tree based flooding and multicasting
  - 1:1 (between two devices or between gateway and a device)

Introduction of The Simulator

- Simulator
  - network simulator 3.17 with lr-wpan model
    - Event driven simulator
- Implanted features of the lr-wpan in ns-3
  - IEEE 802.15.4 non-beacon/beacon mode
  - IEEE 802.15.4m TMCTP
- Simulator verification methods
  - Wireshark packet tracing

Simulation Setup: MAC/PHY

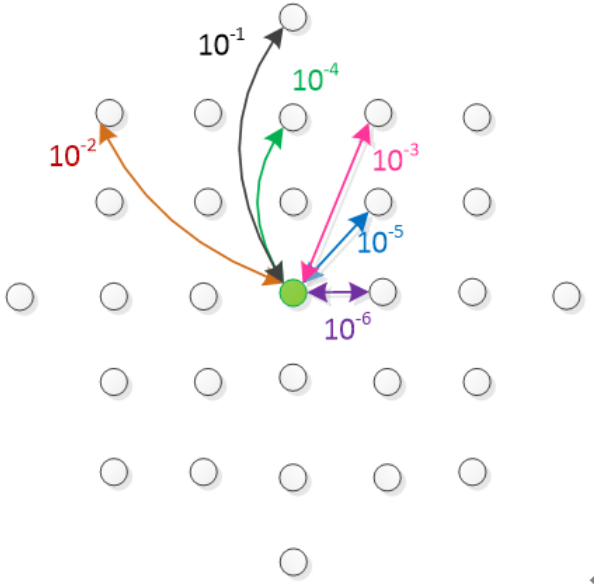
- MAC/PHY
  - IEEE 802.15.4 non beacon enabled PAN
  - IEEE 802.15.4m TMCTP (Beacon enabled PAN) : PANN interval: 60 seconds.
  - Frequency and modulation: 2.4GHz O-QPSK
  - Data rate: 250Kb/s, Fading model: Rayleigh
  - Processing delay: Uniform Random distribution (min:10, max:2000) milliseconds.

Beacon enabled PAN parameters

Type	Value
BO(Beacon Order)	6
SO(Superframe Order)	4
EO (TMCTP Extended Order)	4
Beacon interval	0.983sec
Slot duration	0.0154 s
aBaseSuperframeDuration	960
aNumSuperframeSlots	16
Simulation time	1 day
Traffic size	100 byte / 30 min.

Simulation Setup: Topology

- Topology
  - Grid, Random topology
- Network size
  - 11x11 nodes : 138 nodes
    - 121 nodes + 17 Coordinators
  - 33x33 nodes : 1315 nodes
    - 1081 nodes + 234 coordinators
- Location of the concentrator
  - Center of the network



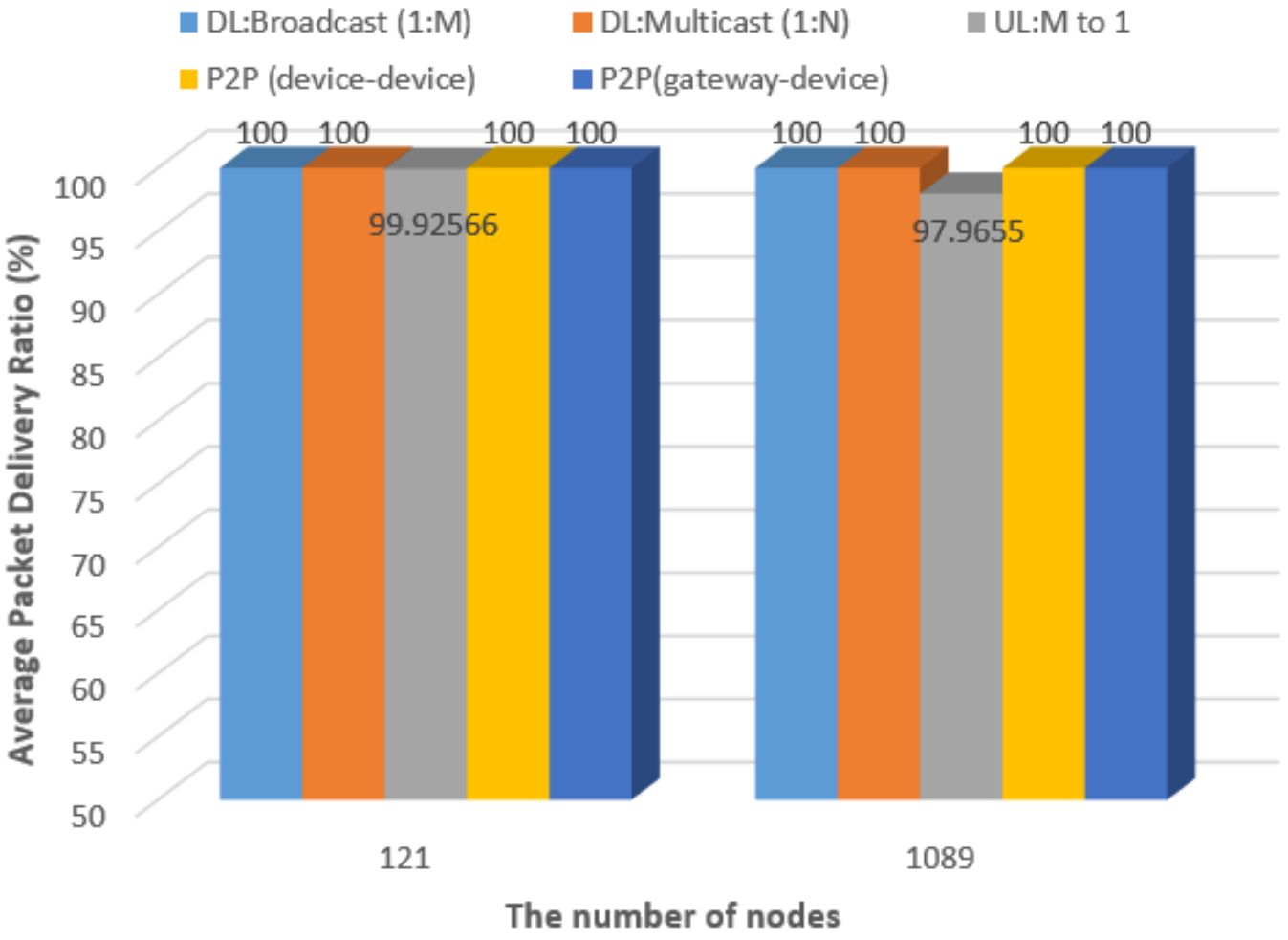
Near by 28 nodes in the transmission range of node

Simulation Setup: Application Setting

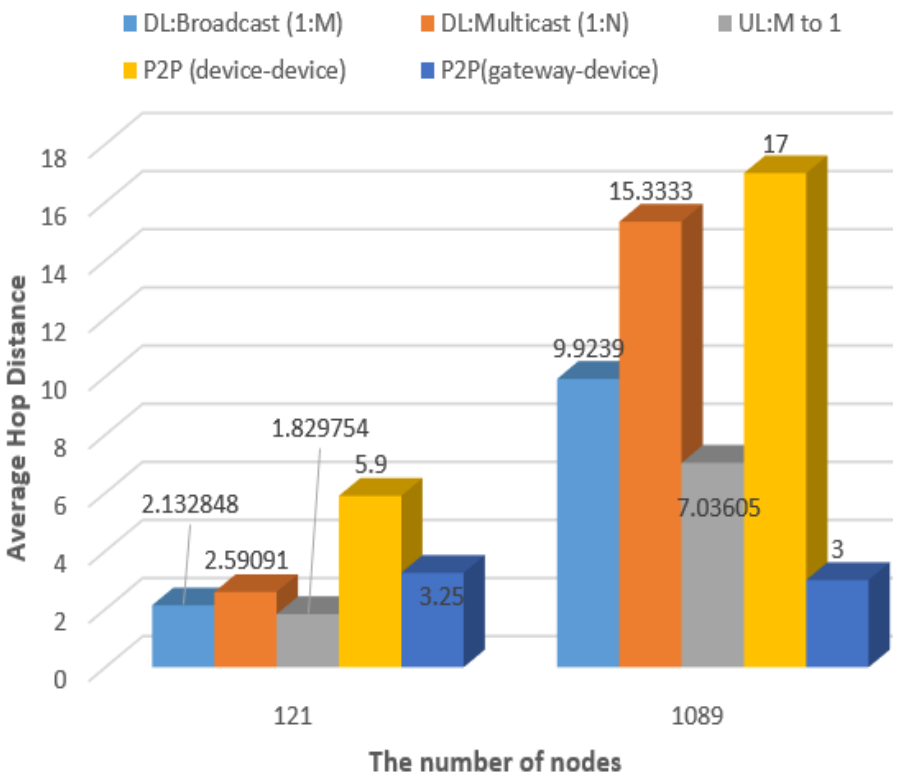
- Traffic size: 100 byte per 30 min.
- Uplink and P2P
  - transmission from one of (m-1) sources (device) to 1 destination (gateway)
  - transmission from 1 source (device) to 1 destination (device)
- Downlink
  - Unicast P2P
    - Gateway to a device
  - Multicast (transmission from 1 source to m destinations (m < M -1))
    - m=5 for M=121
    - m=10 for M =1089
  - Broadcast
    - Gateway to entire devices

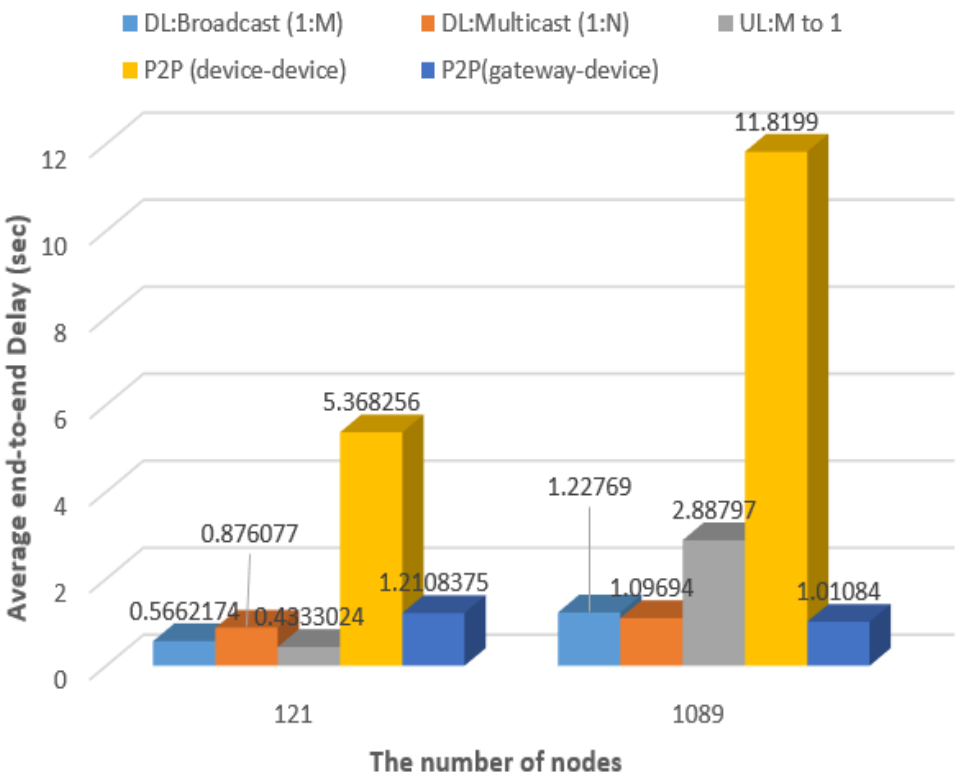
NON-BEACON WPAN

Packet Delivery Ratio

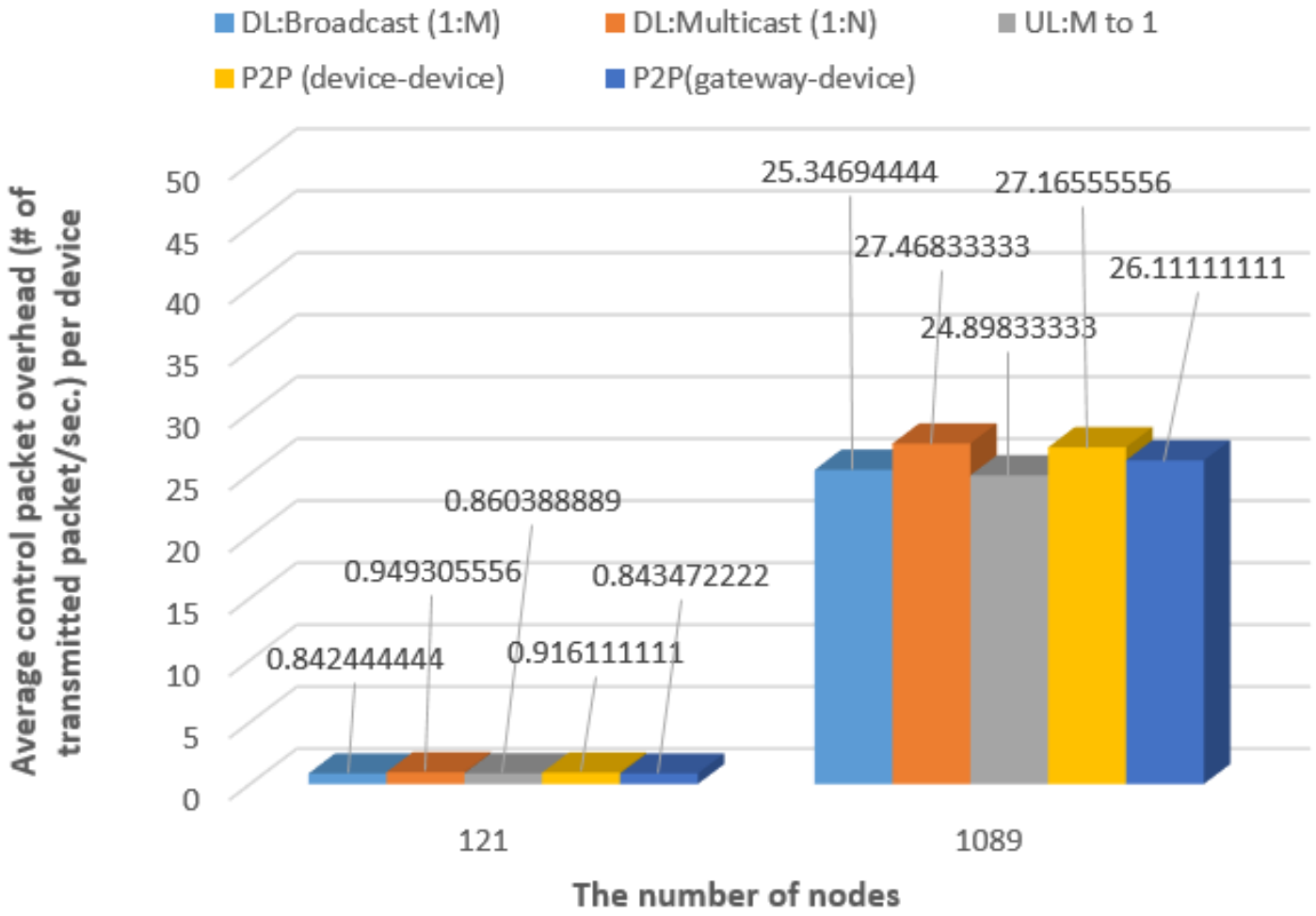


Average Hop Distance and E2E Delay

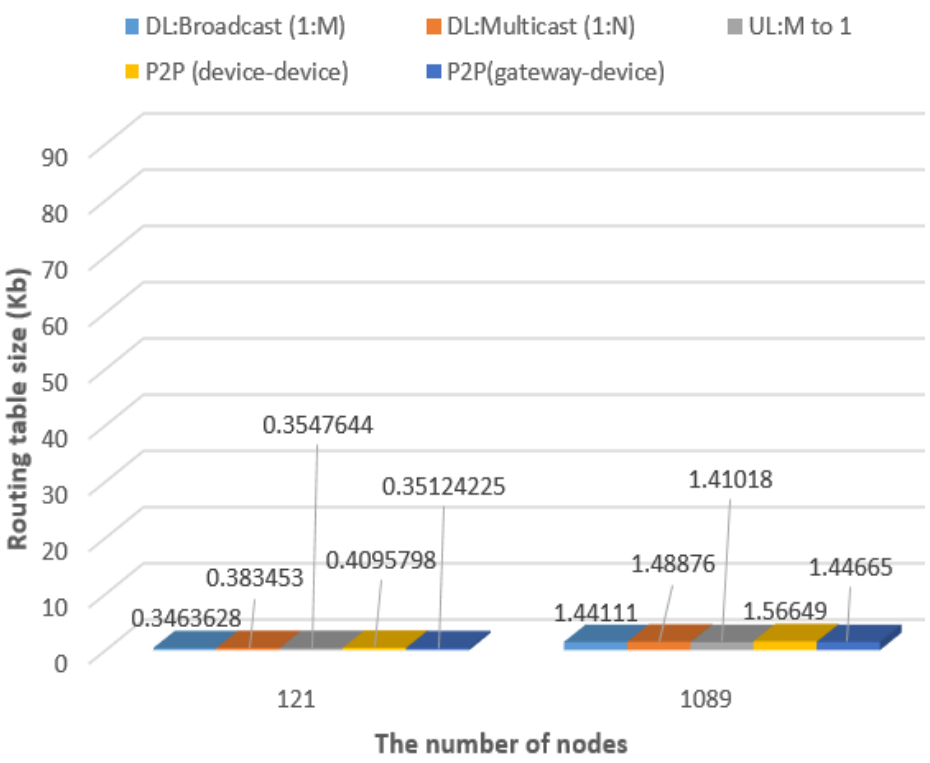




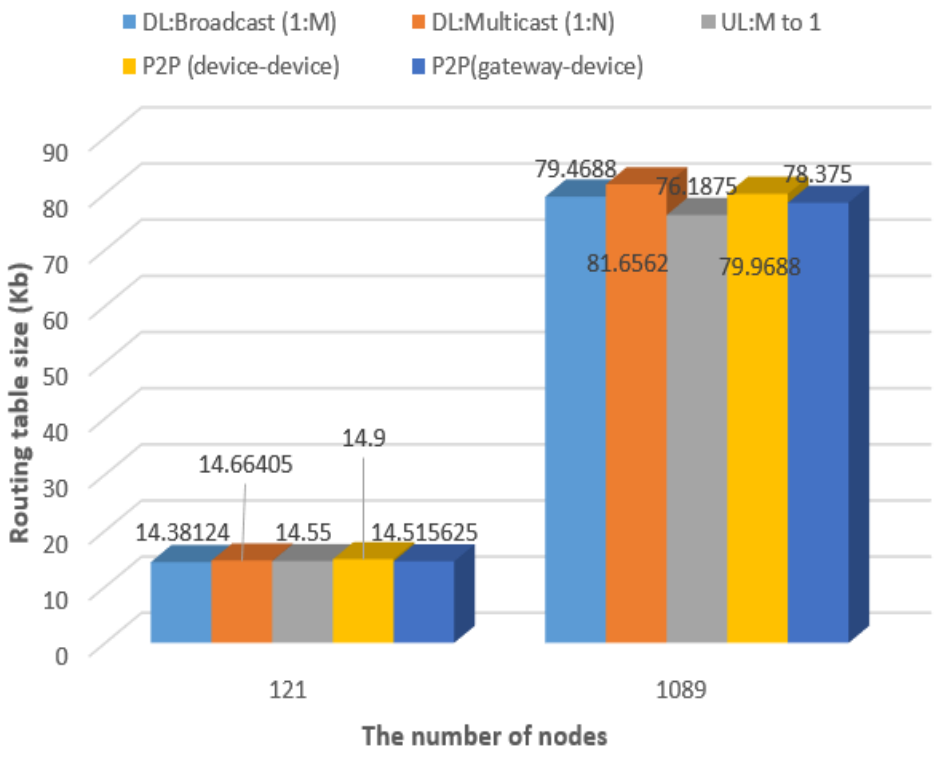
Control Packet Overhead per Device



Memory Usage

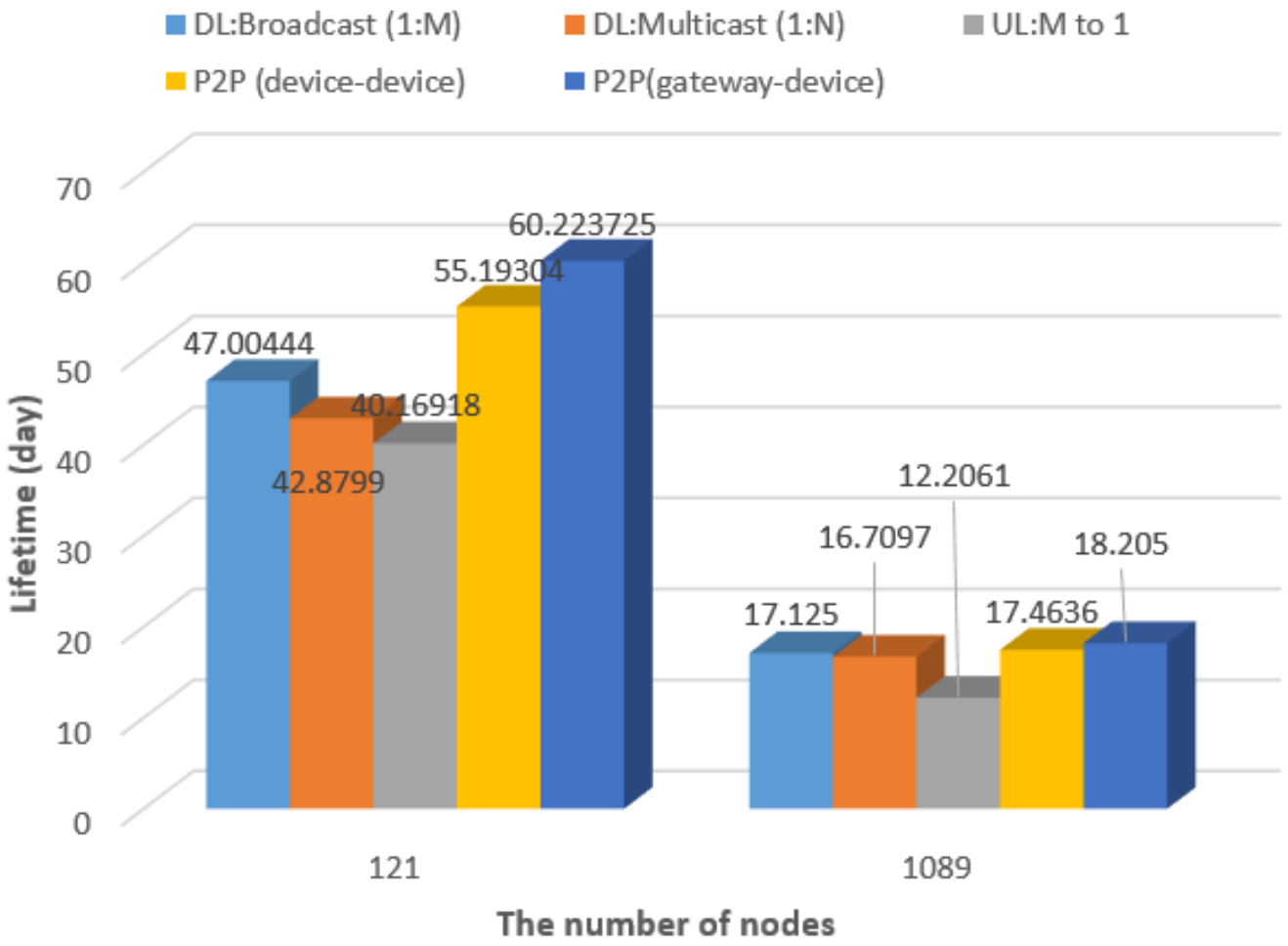


Device



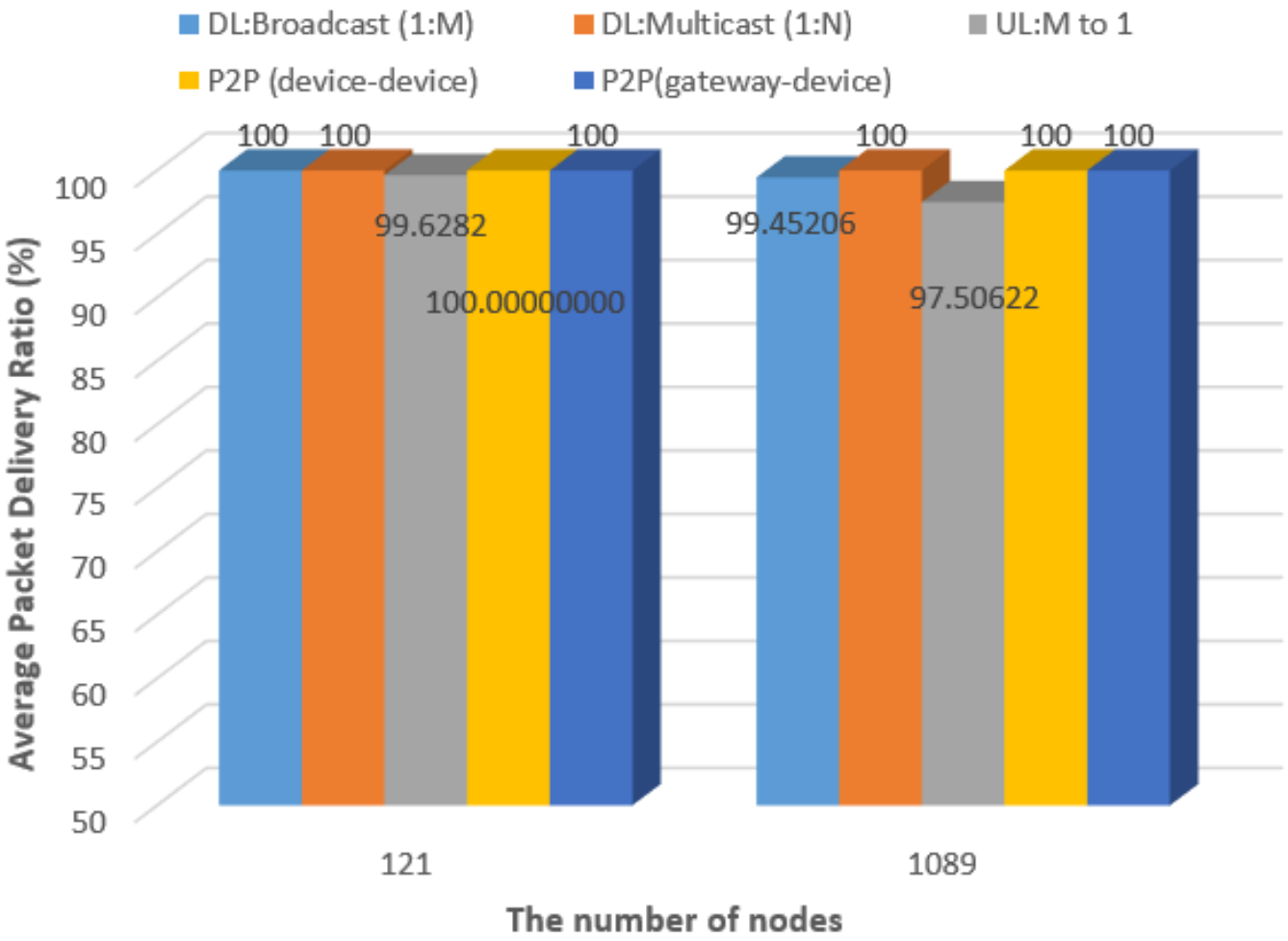
Gateway

Energy Consumption and Life Time

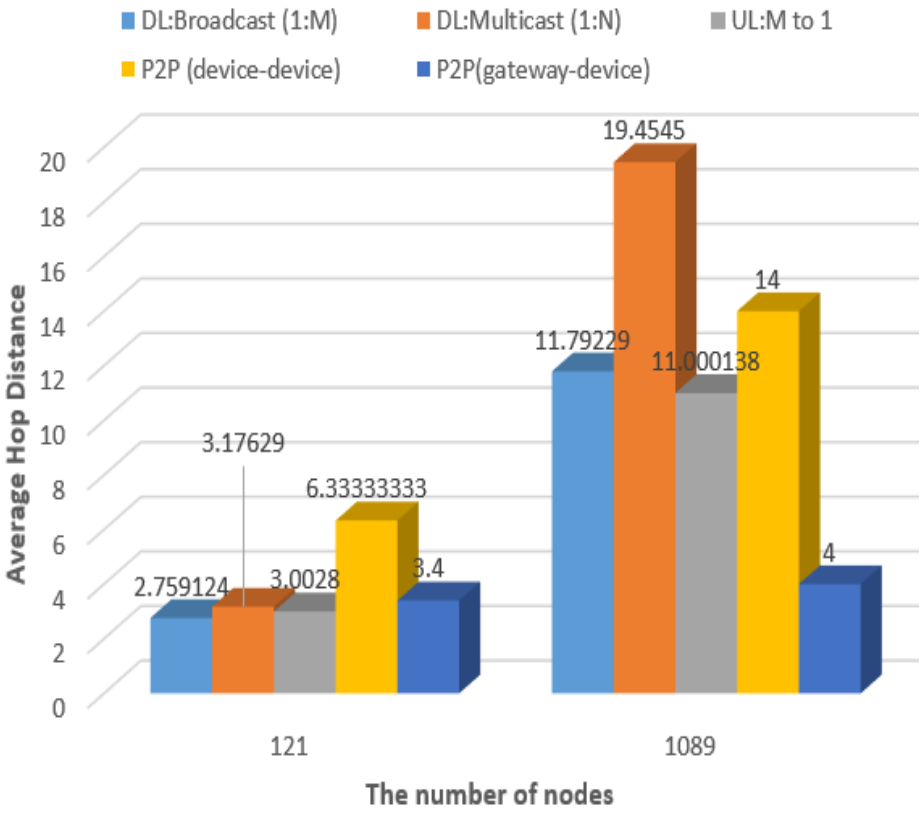


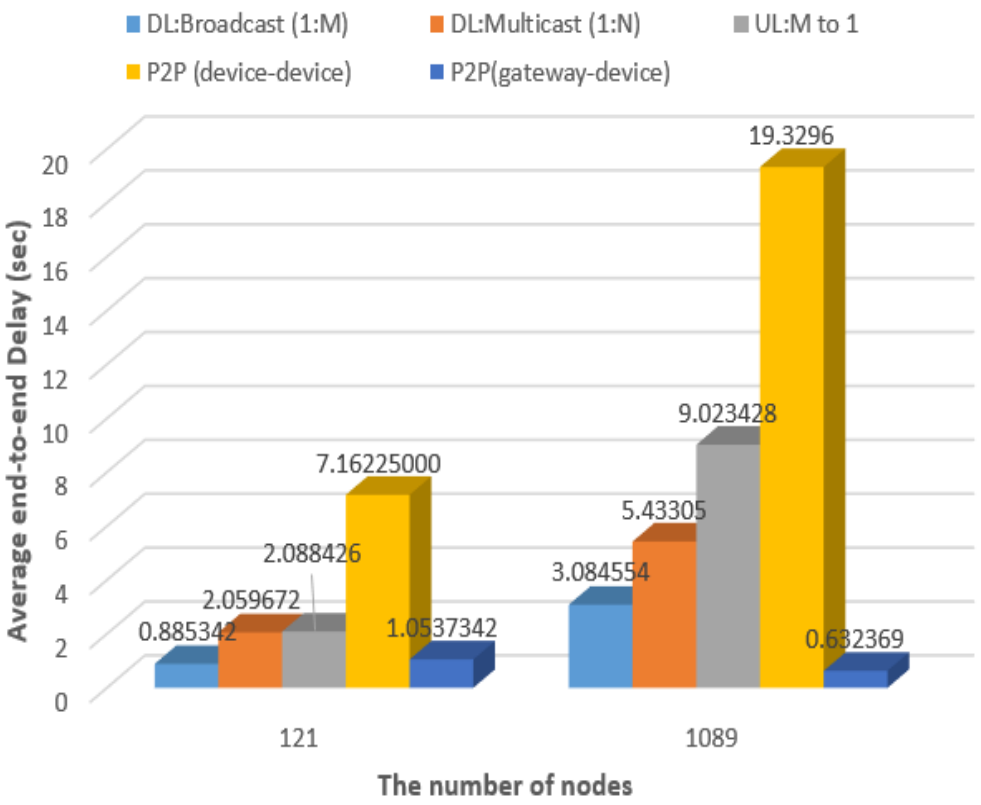
BEACON ENABLED WPAN with multi-channel environment (TMCTP)

Packet Delivery Ratio

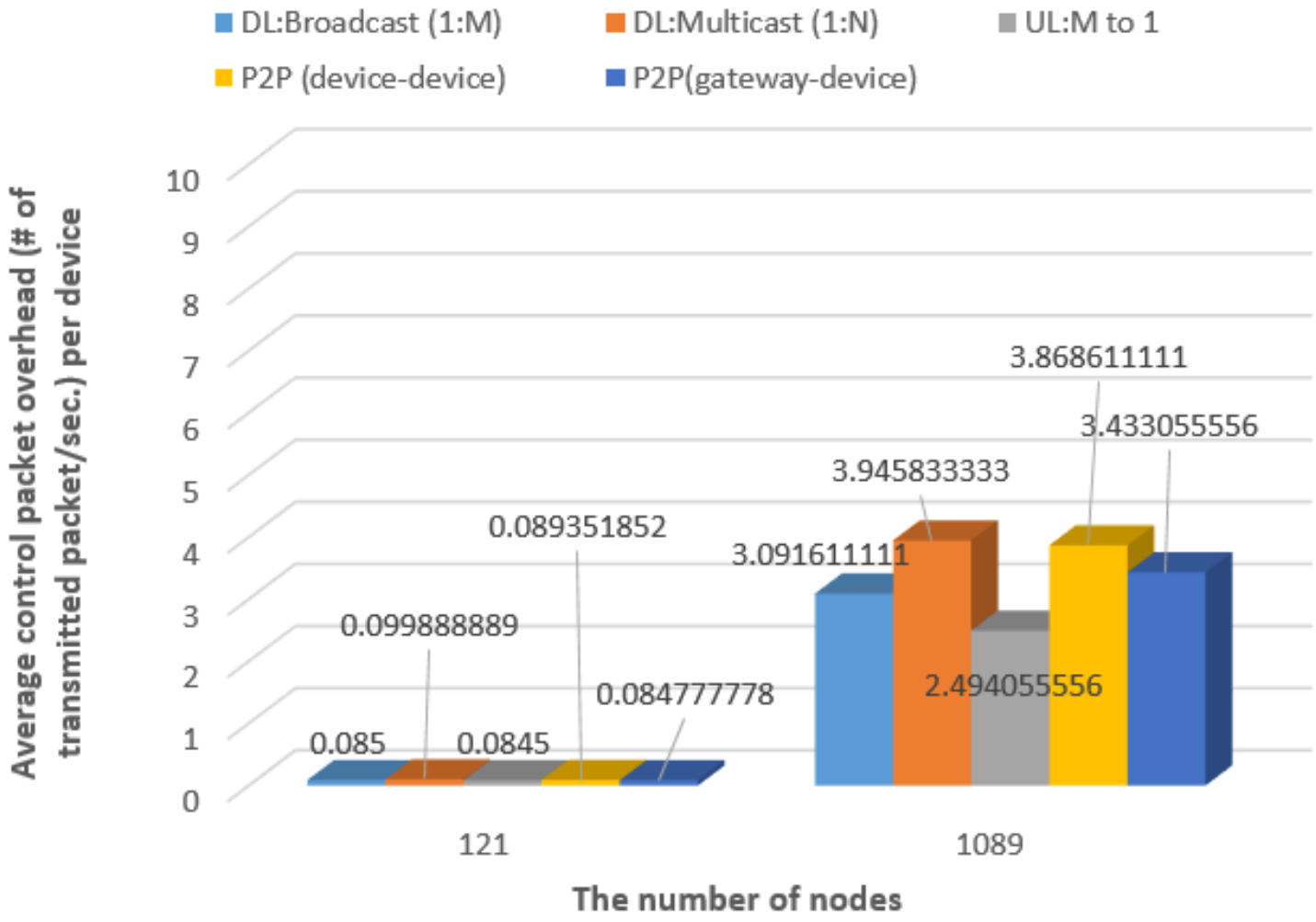


Average Hop Distance and E2E Delay

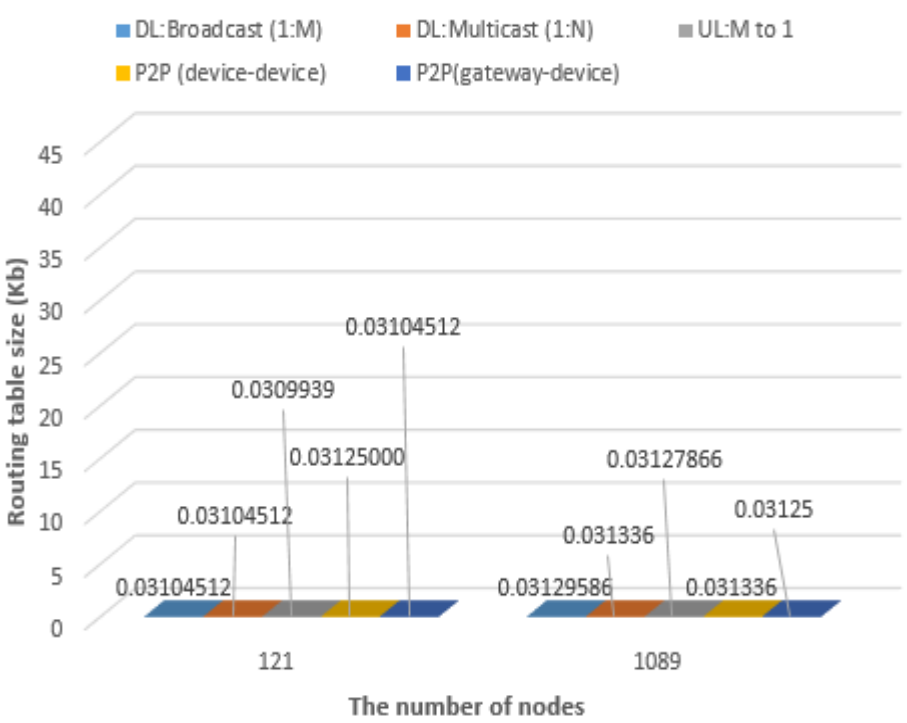




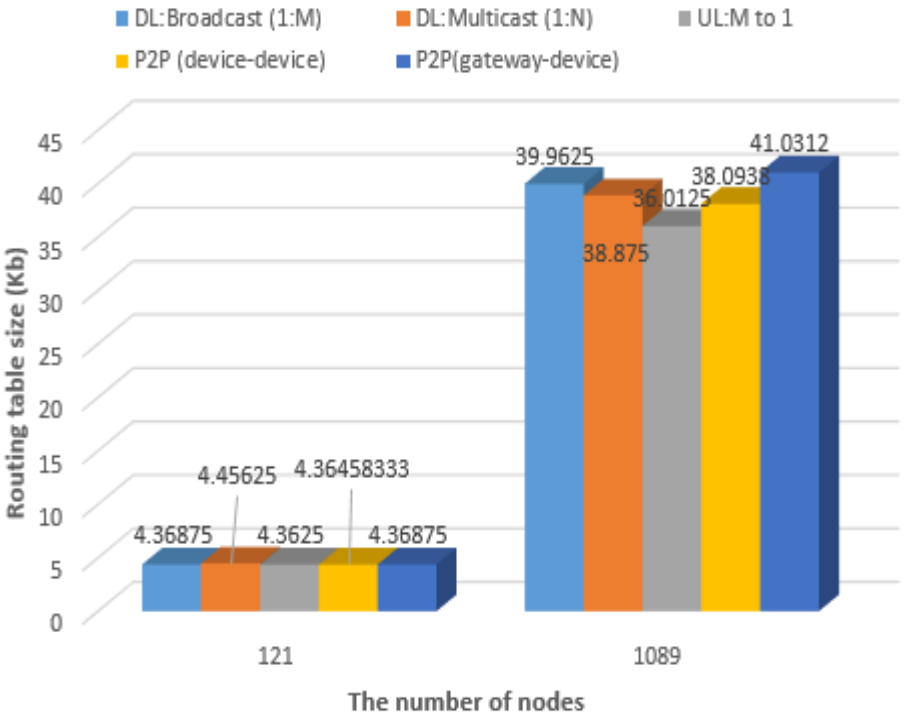
Control Packet Overhead Per Device



Memory Usage

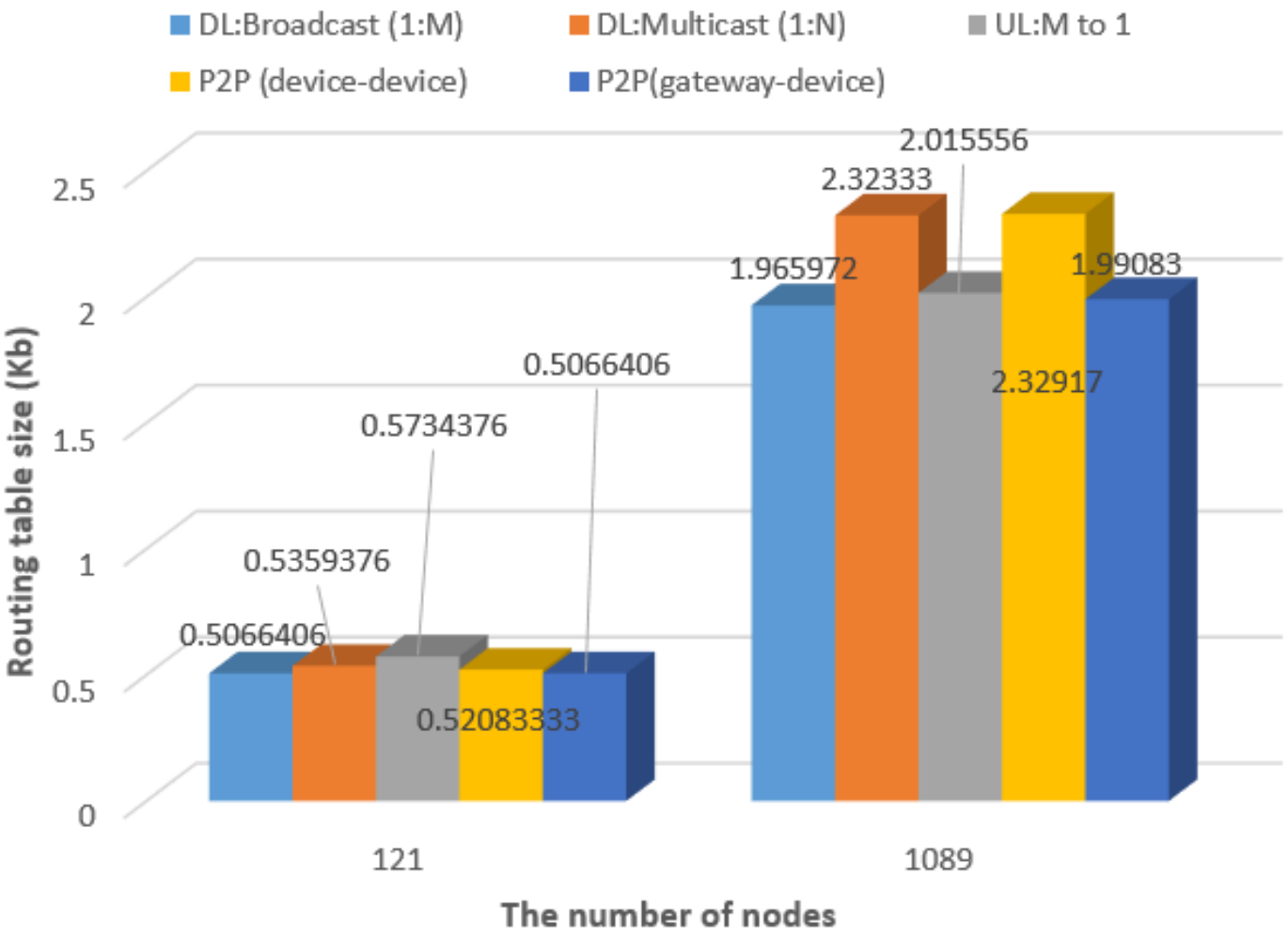


Device

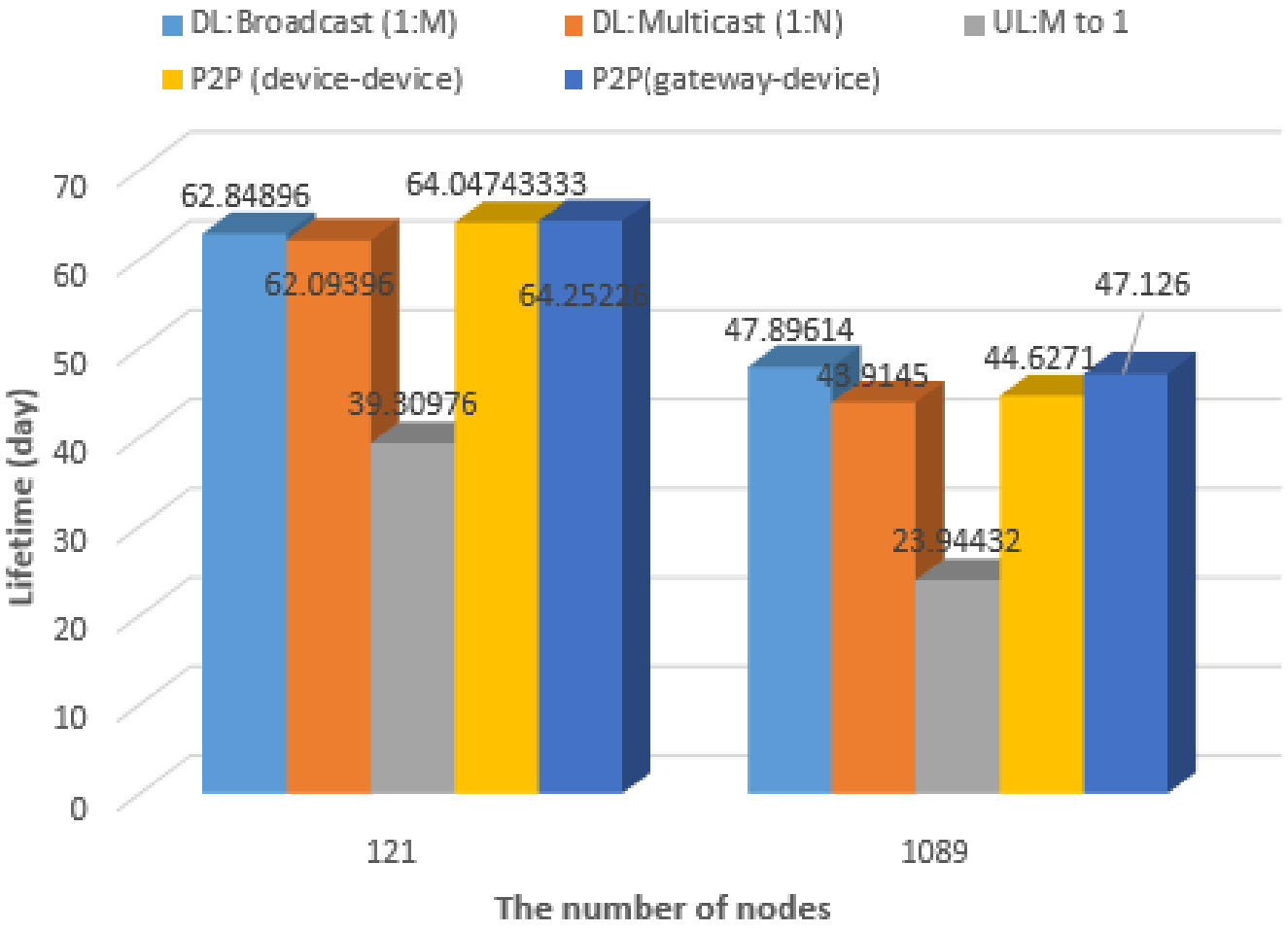


Gateway

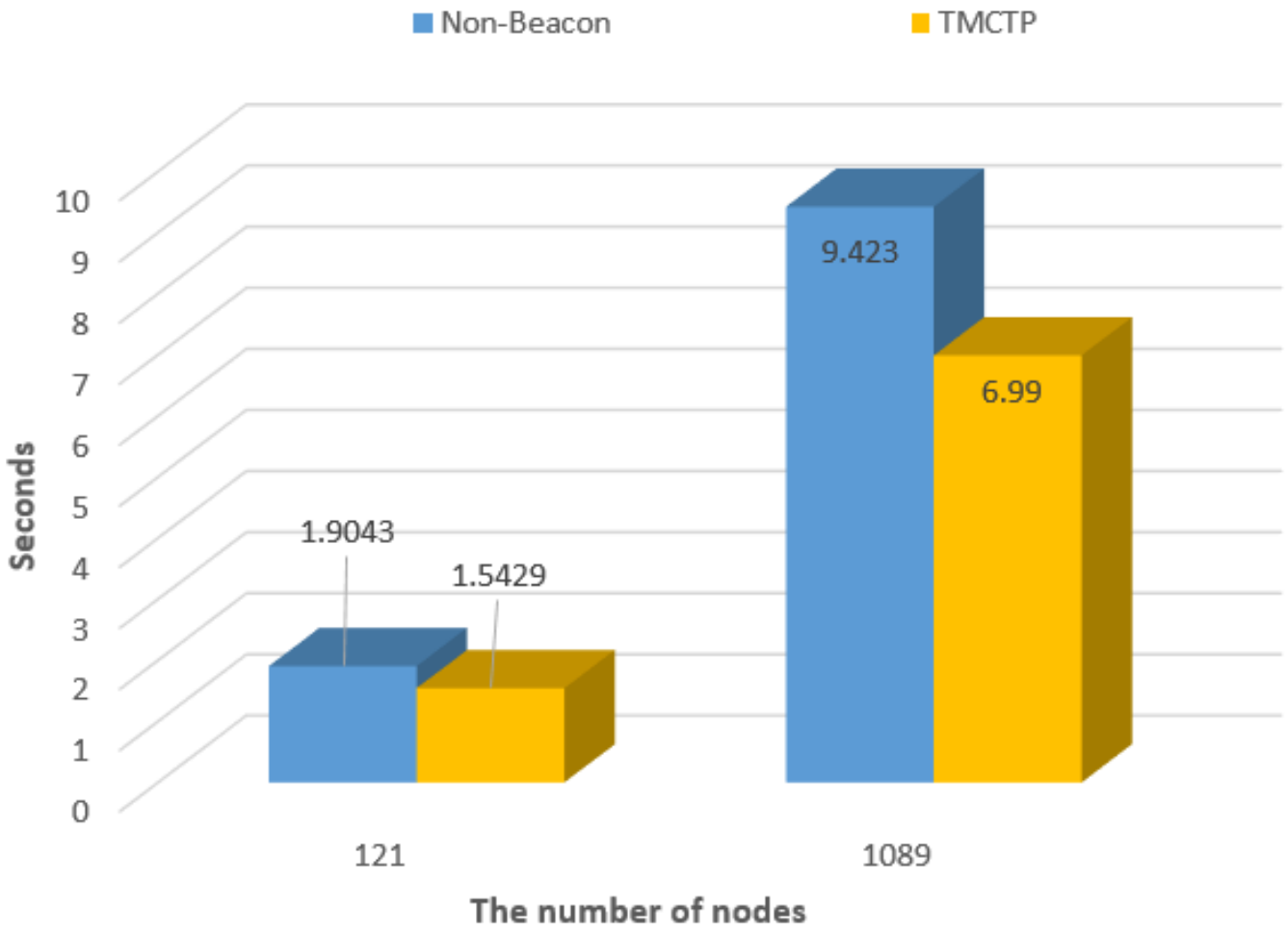
Memory Usage: Coordinator



Energy Consumption and Life Time



Appendix 1: Route Recovery Time



Appendix 2: Energy Consumption

DL:Broadcast (1:M)	numNodes:	Average TxTime(sec):	Average RxTime(sec):	Average IdleTime(sec):	Average InactiveTime (sec):	Tx wh:	Rx wh:	Idle wh:	Inactive wh:	Avg. wH per device:	LifeTime (day):
B_121	138	0.007763338	5.258612	894.7336	2700	0.00032606	0.001649098	1.50315E-05	4.05E-10	0.001990192	62.84896
B_1089	1315	0.02948566	4.38503	895.5856	2700	0.0012384	0.001375144	1.50459E-05	4.05E-10	0.00262859	47.89614
NB_121	138	0.05130056	1.417498	3598.53	0	0.002154624	0.000444527	6.04553E-05	0	0.002659606	47.00444
NB_1089	1315	0.137478	4.67089	3595.19	0	0.00577406	1.46E-03	6.04E-05	0.00E+00	0.00729925	17.125
DL:Multicast (1:N)											
B_121	138	0.008314758	5.262006	894.7296	2700	0.00034922	0.001650164	1.50315E-05	4.05E-10	0.002014416	62.09396
B_1089	1315	0.035337	4.29604	895.669	2700	0.00148415	0.00134724	1.50472E-05	4.05E-10	0.00284644	43.9145
NB_121	138	0.056398075	1.55529	3598.39	0	0.00236872	0.000487739	6.05E-05	0	0.00291691	42.8799
NB_1089	1315	0.140896	4.79154	3595.07	0	0.00591764	0.00150263	6.04E-05	0	0.00748067	16.7097
UL:M to 1											
B_121	138	0.03510584	5.420308	894.5444	2700	0.001474446	0.001699808	1.50283E-05	4.05E-10	0.003189282	39.30976
B_1089	1315	0.08961	4.736242	895.1742	2700	0.003763618	0.001485284	1.50389E-05	4.05E-10	0.005263944	23.94432
NB_121	138	0.0599812	1.704078	3598.234	0	0.002519206	0.000534398	6.04504E-05	0	0.003114058	40.16918
NB_1089	1315	0.192762	6.64667	3593.16	0	0.00809602	0.00208439	6.04E-05	0	0.0102408	12.2061
P2P (device-device)											
B_121	138.00000000	0.00703420	5.23999333	894.75300000	2700.00000000	0.00029544	0.00164326	0.00001503	0.00000000	0.00195373	64.04743333
B_1089	1315	0.0342707	4.29392	895.672	2700	0.00143937	0.00134657	1.50E-05	4.05E-10	0.00280099	44.6271
NB_121	138	0.04352868	1.207944	3598.75	0	0.001828206	0.000378811	6.0459E-05	0	0.002267474	55.19304
NB_1089	1315	0.134702	4.59136	3595.27	0	0.00565749	0.00143985	6.04E-05	0	0.00715774	17.4636
P2P(gateway-device)											
B_121	138	0.006778852	5.251698	894.7414	2700	0.000284712	0.001646932	1.50317E-05	4.05E-10	0.001946674	64.25226
B_1089	1315	0.0307292	4.29461	895.675	2700	0.00129063	0.00134679	1.50473E-05	4.05E-10	0.00265247	47.126
NB_121	138	0.03973145	1.1107375	3598.8475	0	0.00166872	0.000348327	6.04607E-05	0	0.00207751	60.223725
NB_1089	1315	0.129083	4.41436	3595.46	0	0.00542149	0.00138434	6.04037E-05	0	0.00686624	18.205

Appendix 3: Memory Usage

DL:Broadcast (1:M)	Average PC table size:	Average PC table size (kB):	Average Devices table size:	Average Devices table size (kB):	SPC table size:	SPC table size (kB):	ControlPktNumber(/H):
B_121	16.2125	0.5066406	0.9934424	0.03104512	139.8	4.36875	306
B_1089	62.91112	1.965972	1.001466	0.03129586	1278.8	39.9625	11129.8
NB_121	0	0	11.0836	0.3463628	460.2	14.38124	3032.8
NB_1089	0	0	46.1156	1.44111	2543	79.4688	91249
DL:Multicast (1:N)							
B_121	17.15	0.5359376	0.9934424	0.03104512	142.6	4.45625	359.6
B_1089	74.3467	2.32333	1.00275	0.031336	1244	38.875	14205
NB_121	0	0	12.2705	0.383453	469.25	14.66405	3417.5
NB_1089	0	0	47.6404	1.48876	2613	81.6562	98886
UL:M to 1							
B_121	18.35	0.5734376	0.991803	0.0309939	139.6	4.3625	304.2
B_1089	64.49778	2.015556	1.0009192	0.03127866	1152.4	36.0125	8978.6
NB_121	0	0	11.35244	0.3547644	465.6	14.55	3097.4
NB_1089	0	0	45.1257	1.41018	2438	76.1875	89634
P2P (device-device)							
B_121	16.66666667	0.52083333	1	0.0312500	139.66	4.36458	321.6
B_1089	74.5333	2.32917	1.00275	0.031336	1219	38.0938	13927
NB_121	0	0	13.10658	0.4095798	476.8	14.9	3298
NB_1089	0	0	50.1275	1.56649	2559	79.9688	97796
P2P(gateway-device)							
B_121	16.2125	0.5066406	0.9934424	0.03104512	139.8	4.36875	305.2
B_1089	63.7067	1.99083	1	0.03125	1313	41.0312	12359
NB_121	0	0	11.23975	0.35124225	464.5	14.515625	3036.5
NB_1089	0	0	46.2927	1.44665	2508	78.375	94000

Appendix 4: QoS Comparison

DL:Broadcast (1:M)	Average HopCount :	num_send:	num_recv:	goodput (kbps):	MAC throughput (kbps):	PDR:	Average delay:
B_121	2.759124	2	274	0.000834784	0.000931679	100	0.885342
B_1089	11.79229	2	2613.6	0.007962744	0.00888699	99.45206	3.084554
NB_121	2.132848	2	274	0.000834784	0.000931679	100	0.5662174
NB_1089	9.9239	2	2628	0.00800662	0.00893595	100	1.22769
DL:Multicast (1:N)							
B_121	3.17629	2	22	4.81372E-05	5.37246E-05	100	2.059672
B_1089	19.4545	2	66	0.00010054	0.000112209	100	5.43305
NB_121	2.59091	2	22	6.70E-05	7.48E-05	100	0.876077
NB_1089	15.3333	2	66	0.00010054	0.000112209	100	1.09694
UL:M to 1							
B_121	3.0028	268.2	267.2	0.000814067	0.000908557	99.6282	2.088426
B_1089	11.000138	1749.6	1706.4	0.005198818	0.00580225	97.50622	9.023428
NB_121	1.829754	271.6	271.4	0.000826863	0.000922838	99.92566	0.4333024
NB_1089	7.03605	2605	2552	0.00777507	0.00867753	97.9655	2.88797
P2P (device-device)							
B_121	6.33333333	2	2	0.00000609	0.00000680	100	7.16225000
B_1089	14	1	1	3.05E-06	3.40E-06	100	19.3296
NB_121	5.9	2	2	6.09331E-06	6.80057E-06	100	5.368256
NB_1089	17	2	2	6.09E-06	6.80E-06	100	11.8199
P2P(gateway-device)							
B_121	3.4	2	2	6.09331E-06	6.80057E-06	100	1.0537342
B_1089	4	2	2	6.09331E-06	6.80057E-06	100	0.632369
NB_121	3.25	2	2	6.09331E-06	6.80057E-06	100	1.2108375
NB_1089	3	2	2	6.09331E-06	6.80057E-06	100	1.01084