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

Submission Title: [Enhancement to 802.15.4-2006 with Adaptive Frequency Diversity]
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Re: [IEEE P802.15.4e Call For proposal]

Abstract: [This document proposes an enhancement to IEEE 802.15.4-2006 MAC Layer with Adaptive Frequency Diversity for the Reliability and Deterministic Aware Applications]

Purpose: [This document is a response to Item a) better support the industrial markets in IEEE P802.15.SG4e Call for Application on 14 November, 2007]

Enhancement to 802.15.4-2006 with Adaptive Frequency Diversity

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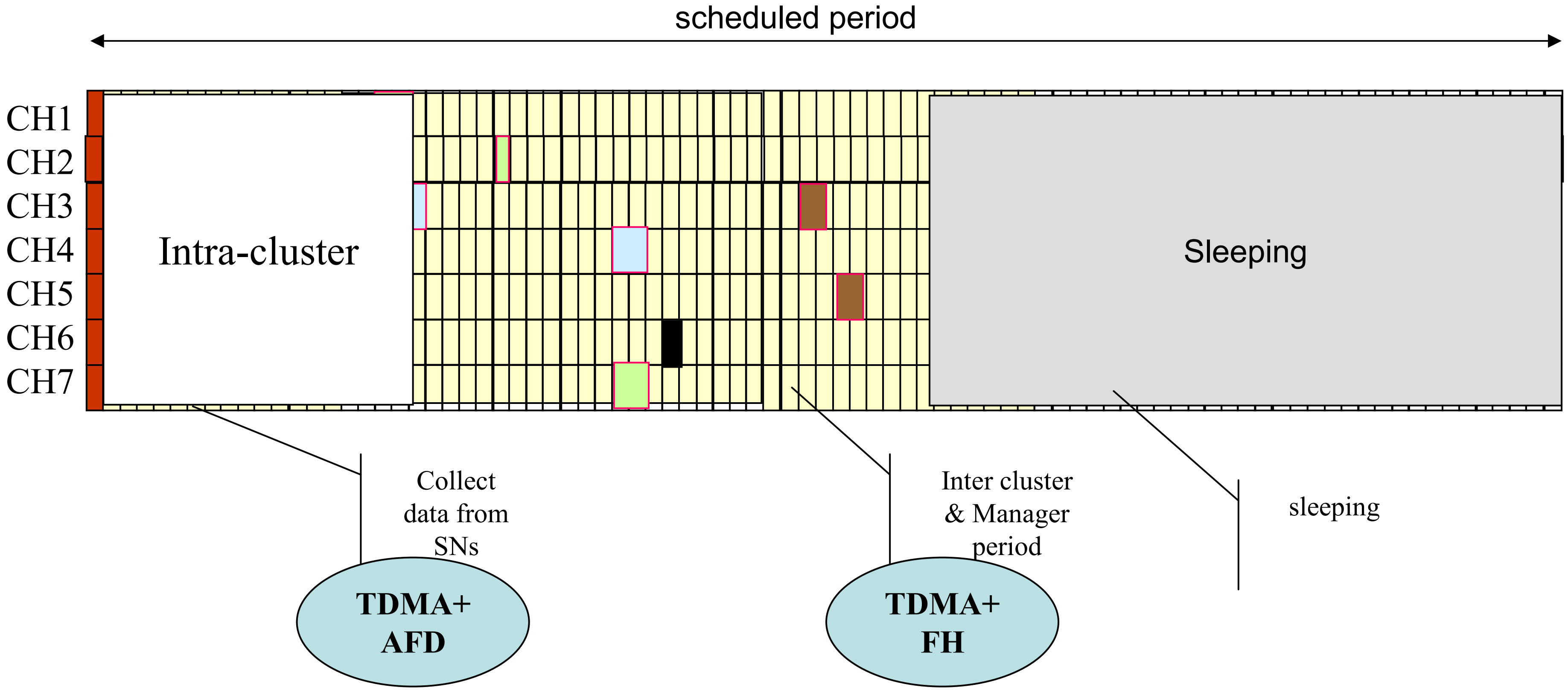
Components.

1. Mesh+Star topology
2. Extended superframe
3. CSMA/TDMA+FDMA during active period
4. **TDMA+FH/AFD during scheduled period with two-stage allocation**

TDMA+FH/AFD in scheduled period



The Inter cluster period and manager period are scheduled by the system manager.

E-Superframe MAC

IEEE 802.15.4	**Proposed Scheme**	**MAC Protocol**
CAP	**CAP**	**CSMA + FDMA**
CFP	**CFP**	**TDMA + FDMA**
Inactive	**Intra-cluster period**	**TDMA + AFD** **(AFD: Adaptive Frequency Diversity)**
	Inter-cluster period **Manager period**	**TDMA+FH**

Note: Difference between AFD with Frequency Hopping (FH)

- FH: Change communication channel according to a scheduled frequency hopping pattern, regardless how the real channel condition is.
- AFD: Change communication channel according to the real channel condition. In another word, bad channel condition, which can be measured with packet drop rate or resend time, triggers the operation of changing channel.

Channel statistics

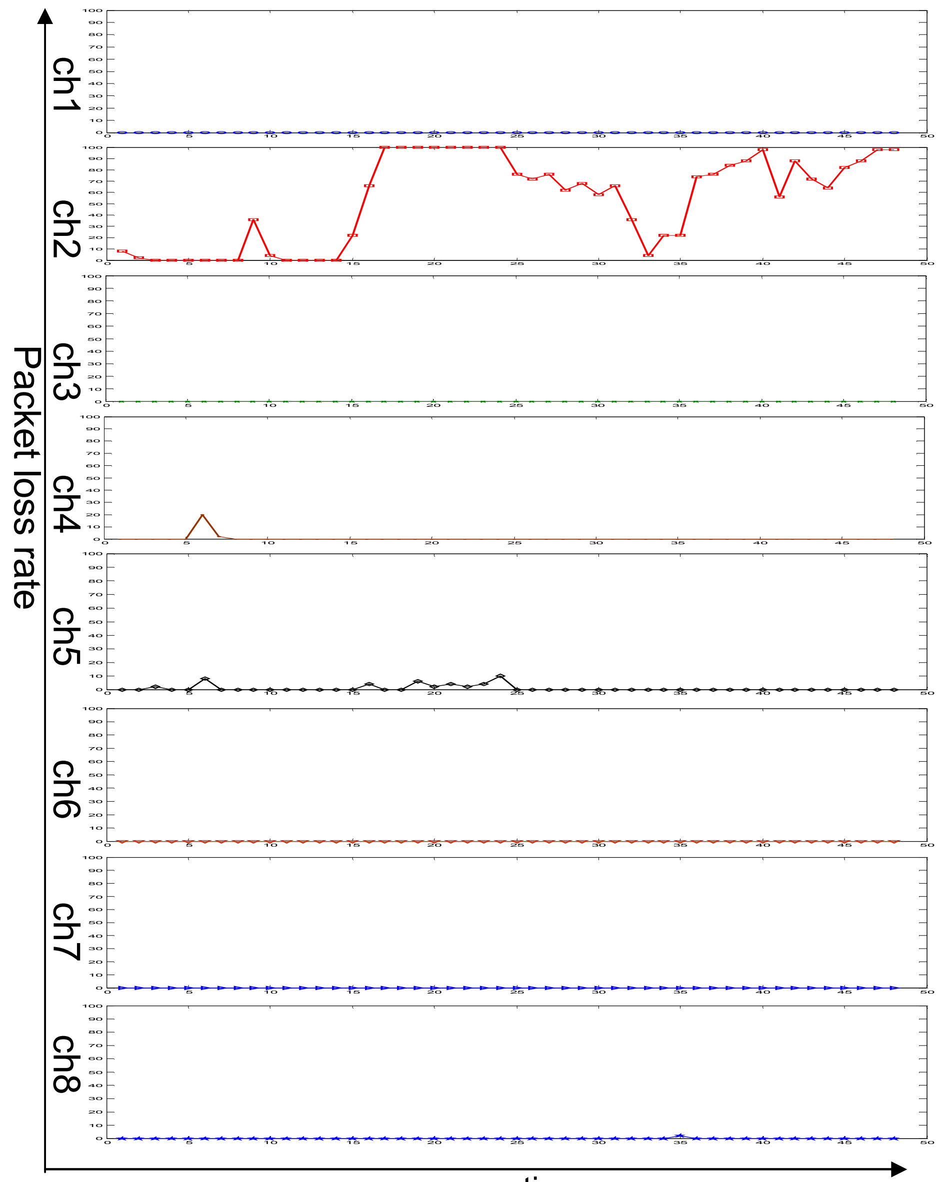
A complete communication include a packet transmitting and an ACK receiving. To describe channel reliability, we define the *packet_loss_rate*, as measured at the transmit end of the path, to be:

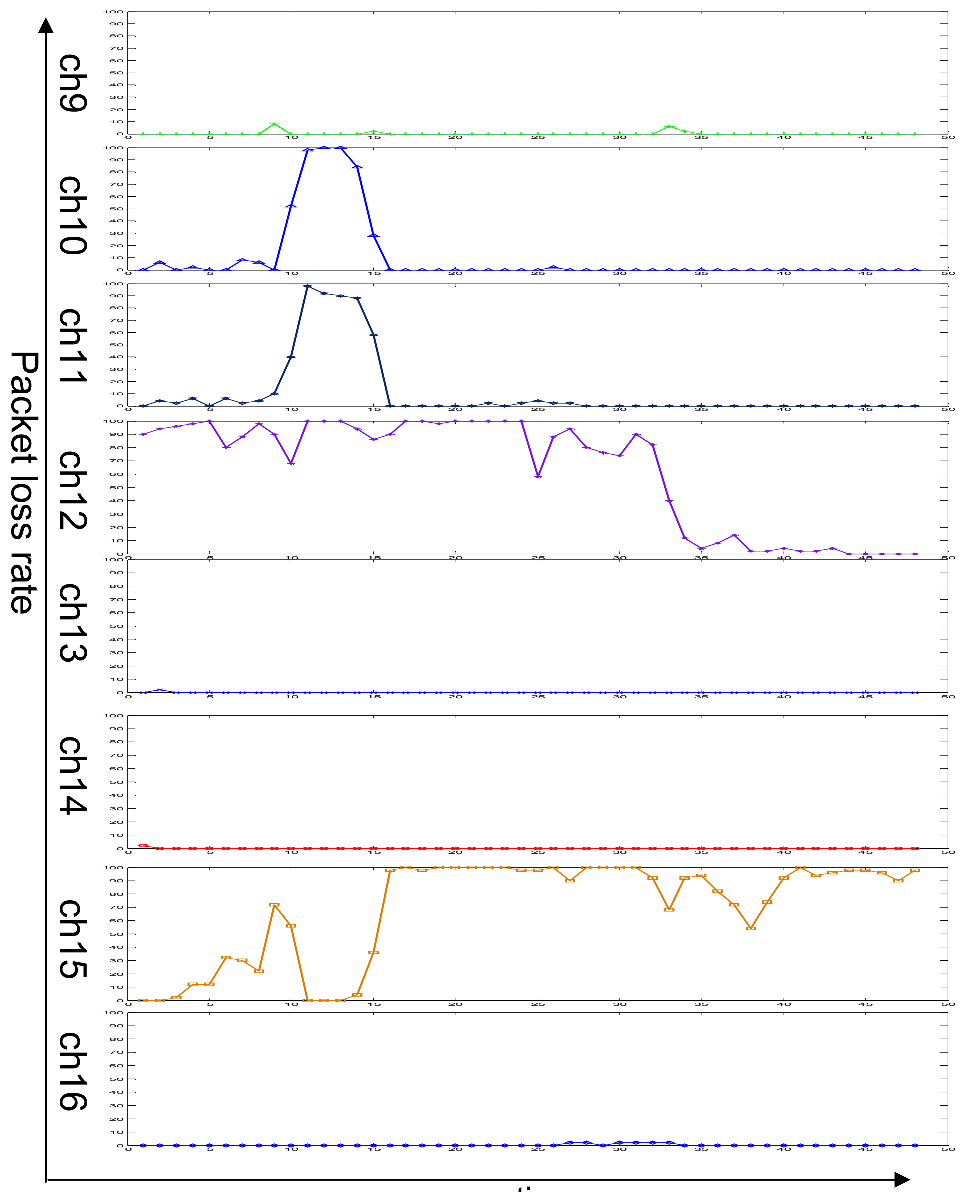
$$Packet\_lost\_rate = \frac{\#NoACK}{\#Transmissions}$$

we measure channel packet loss rate at 50 or 100 transmissions in our tests

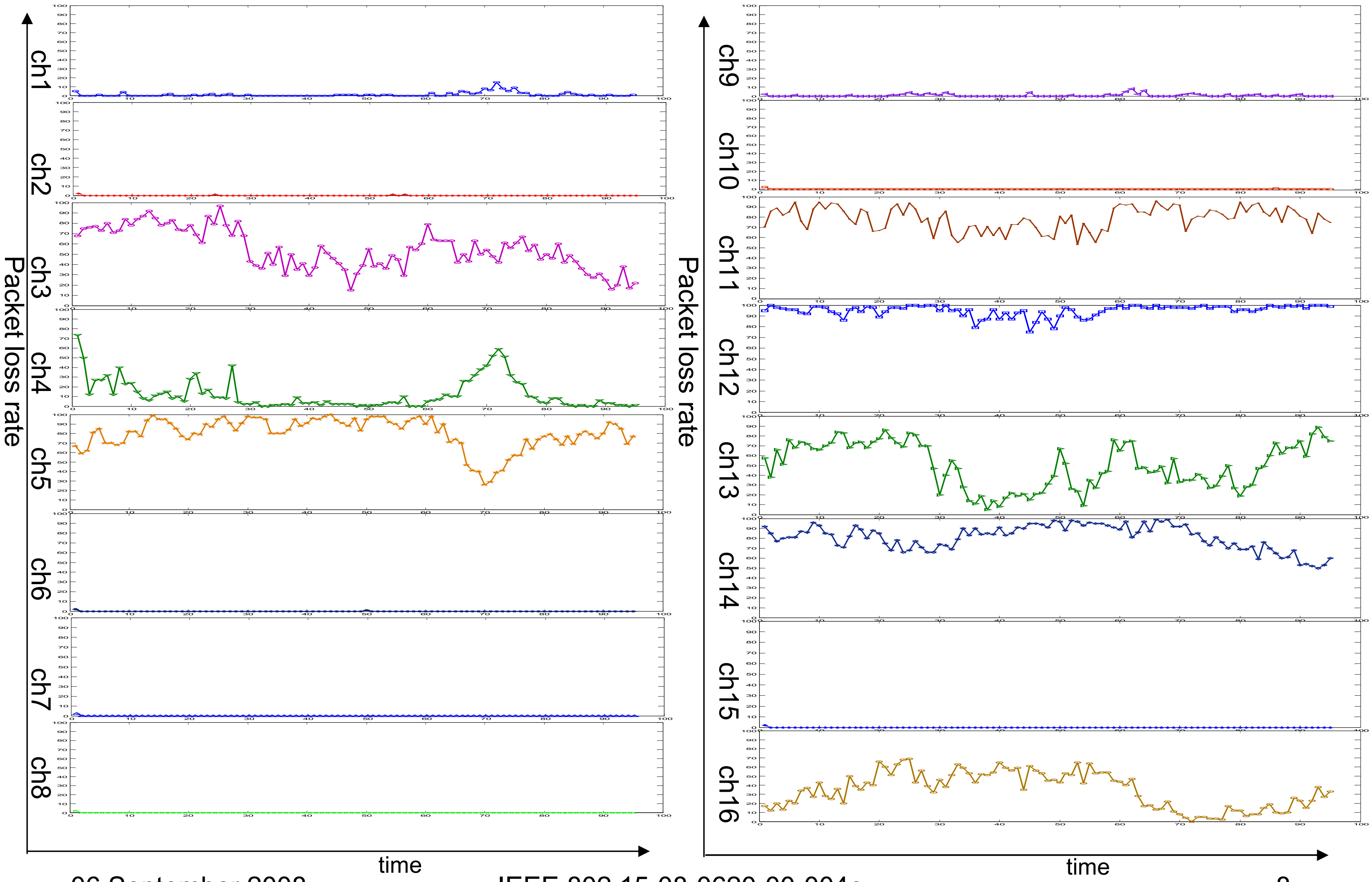
Packet Loss Rate over time in school factory (4 hours)

Different packet loss rate on different channels, low and high packet loss rate last for a relative long stable time on one channel



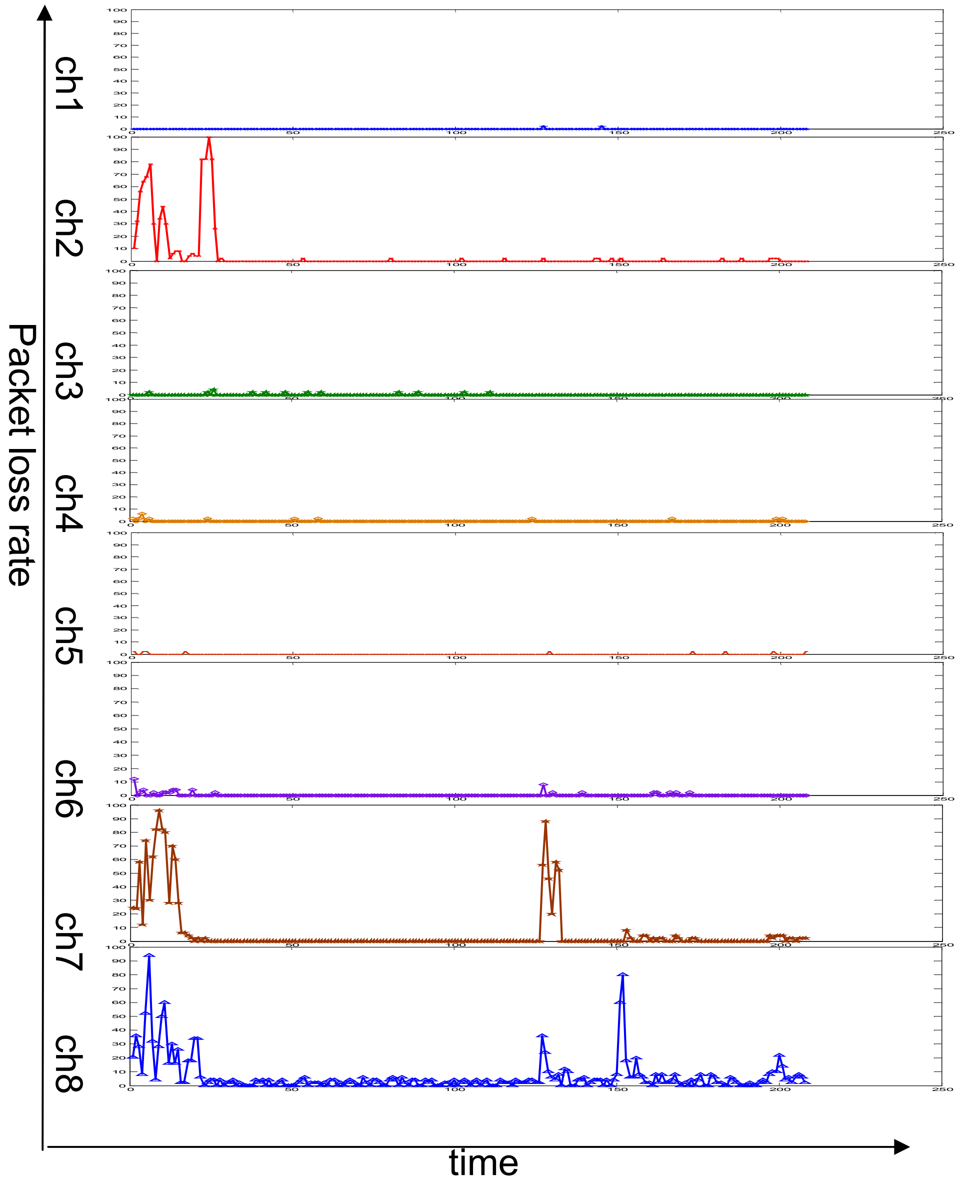


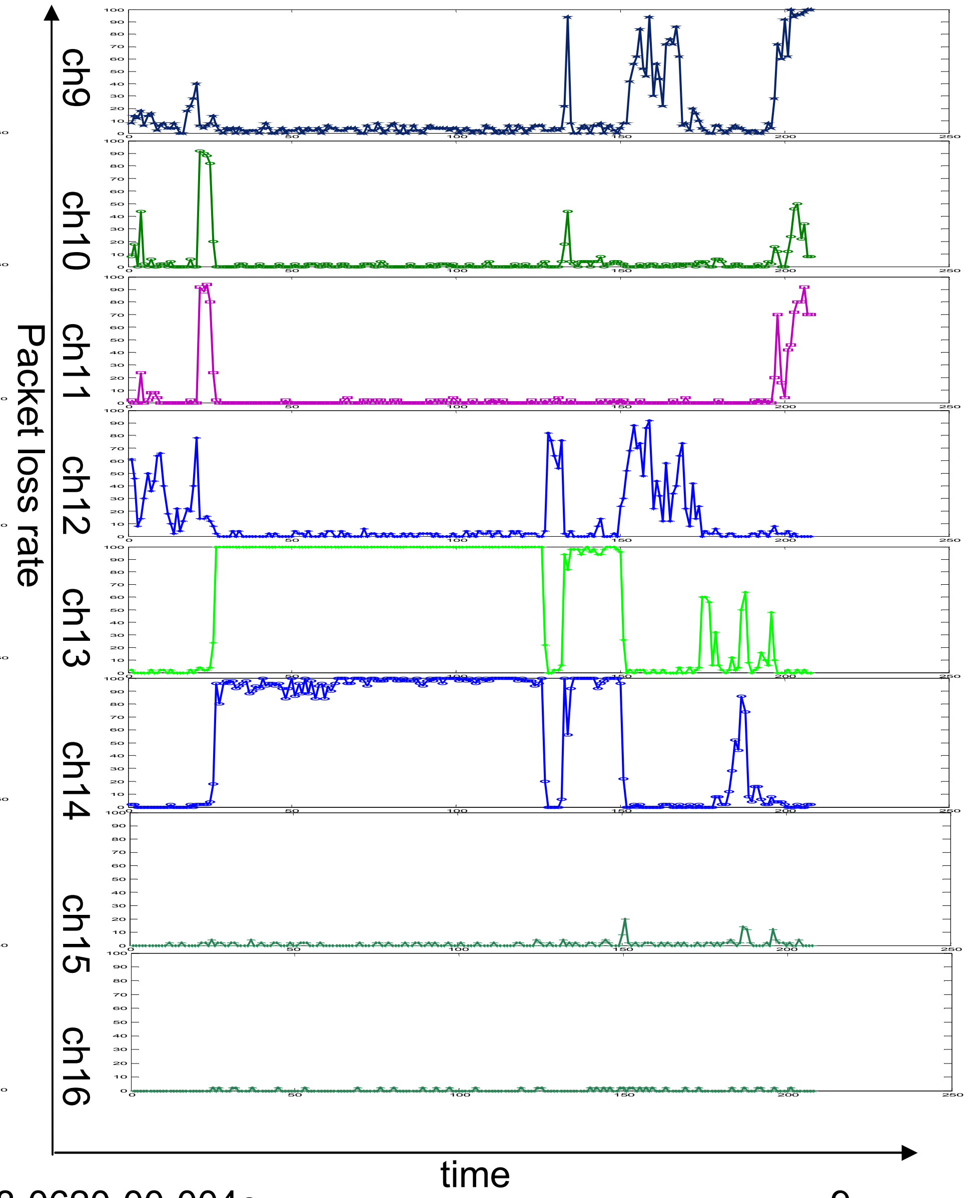
Packet Loss Rate over time in Irion and steel factory (9hours) *The same conclusion as previous test*



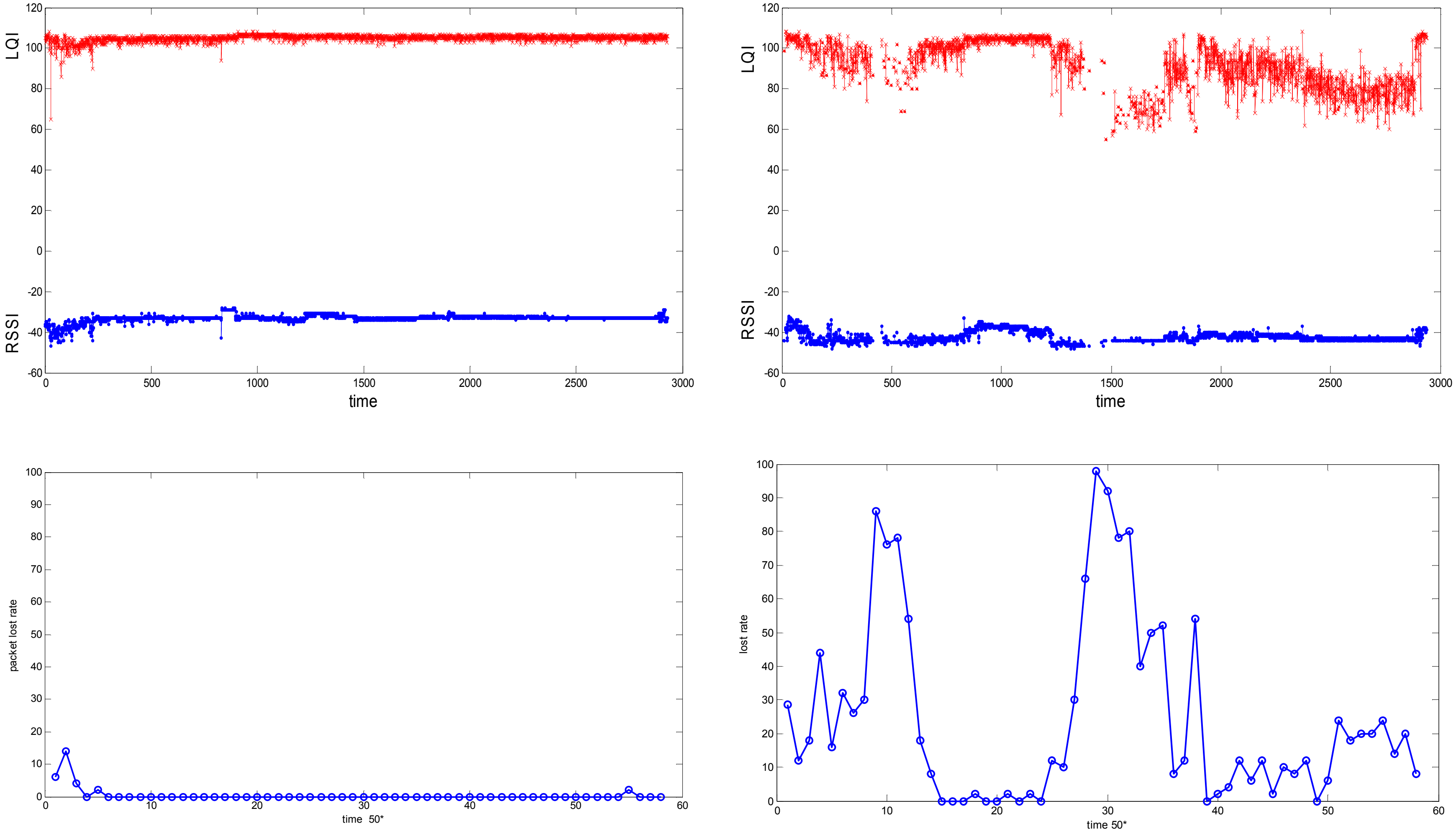
Packet Loss Rate over time in lab (17 hours)

channels have correlations with each other, the same can be found at previous two tests





Relationship between Packet Loss Rate and LQI, RSSI



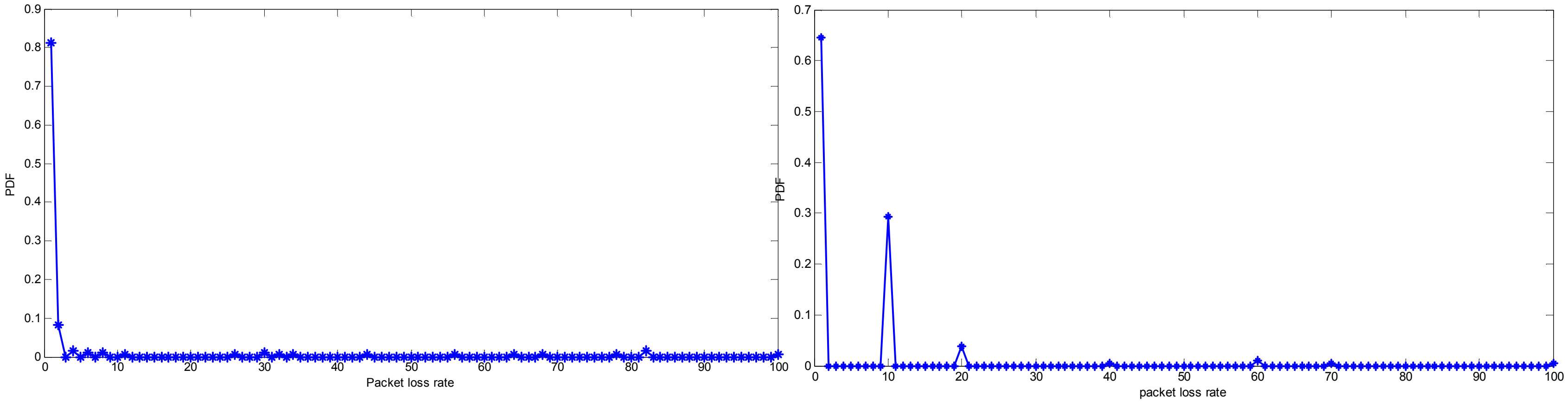
Channel statistics (cont.)

Average packet loss rate of each channel over the test time

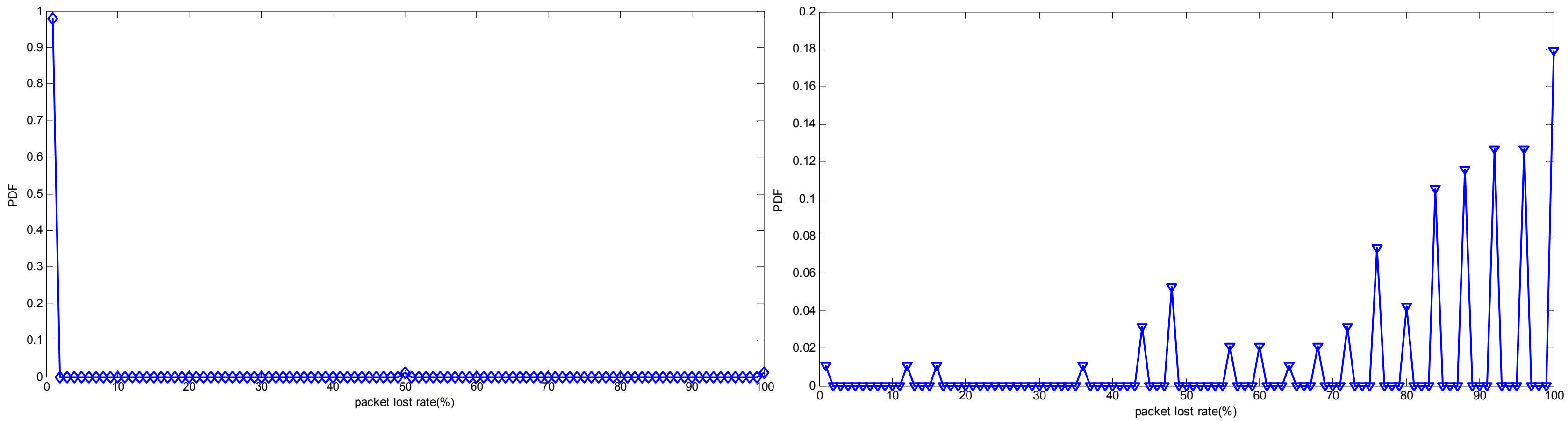
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
test1	E	0	53.5	0	0.46	0.87	0	0	0.04	0.38	10.1	10.6	63.2	0.04	0.04	69.8	0.25
test2	E	1.26	0.05	54.7	12.2	80.1	0.03	0.02	0.02	0.80	0.03	78.8	95.2	50.1	81.2	0.02	34.4
test3	E	0.19	4.23	0.13	0.13	0.08	0.30	5.84	6.58	13.6	4.5	5.6	11.7	59	57.2	1.06	0.36

Channel statistics (cont.)

PDF of packet lost rate



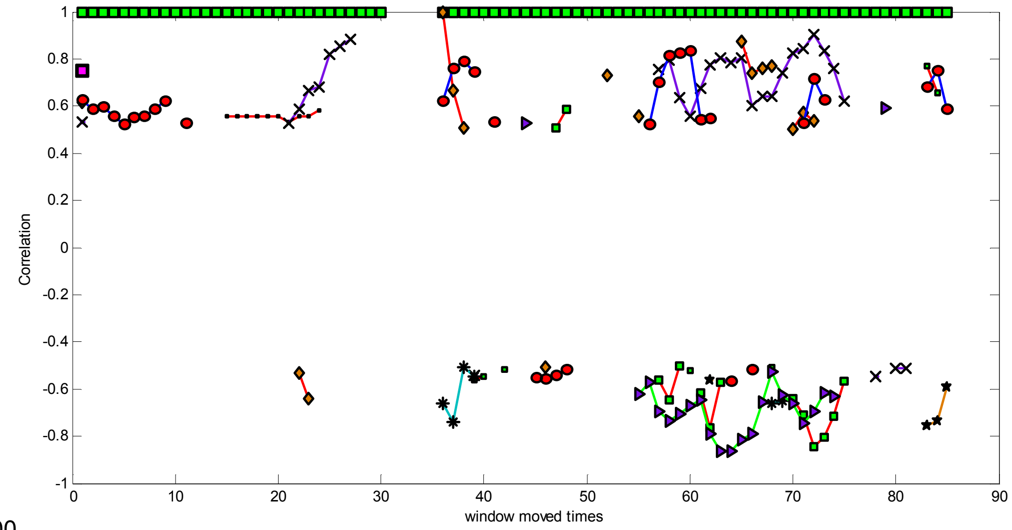
Test3 channel 2 (4.23%) and channel 14 (57.1%)loss rate PDF



Test2 channel 6 (0.03%) and channel 12 (95.26%)loss rate PDF

Channel statistics(cont.)

Correlation coefficients of different channel



ch1	1.00															
ch2	0.72	1.00														
ch3	-0.16	-0.42	1.00													
ch4	0.51	0.71	-0.53	1.00												
ch5	-0.17	-0.25	0.49	-0.56	1.00											
ch6	0.72	1.00	-0.42	0.71	-0.25	1.00										
ch7	0.72	1.00	-0.42	0.71	-0.25	1.00	1.00									
ch8	0.72	1.00	-0.42	0.71	-0.25	1.00	1.00	1.00								
ch9	0.53	0.81	-0.34	0.62	-0.16	0.81	0.81	0.81	1.00							
ch10	0.72	1.00	-0.42	0.71	-0.25	1.00	1.00	1.00	0.81	1.00						
ch11	-0.14	-0.29	0.59	-0.27	0.12	-0.29	-0.29	-0.29	-0.17	-0.29	1.00					
ch12	0.12	-0.03	-0.25	0.08	-0.29	-0.03	-0.03	-0.03	0.00	-0.03	0.20	1.00				
ch13	-0.16	-0.26	0.42	-0.61	0.56	-0.26	-0.26	-0.26	-0.24	-0.26	-0.03	-0.60	1.00			
ch14	0.55	0.27	-0.29	0.31	-0.28	0.27	0.27	0.27	0.14	0.27	-0.29	0.44	-0.25	1.00		
ch15	0.72	1.00	-0.42	0.71	-0.25	1.00	1.00	1.00	0.81	1.00	-0.29	-0.03	-0.26	0.27	1.00	
ch16	-0.23	-0.25	0.03	-0.34	0.31	-0.25	-0.25	-0.25	-0.16	-0.25	-0.40	-0.21	0.48	0.19	-0.25	1.00
	ch1	**ch2**	**ch3**	**ch4**	**ch5**	**ch6**	**ch7**	**ch8**	**ch9**	**ch10**	**ch11**	**ch12**	**ch13**	**ch14**	**ch15**	**ch16**

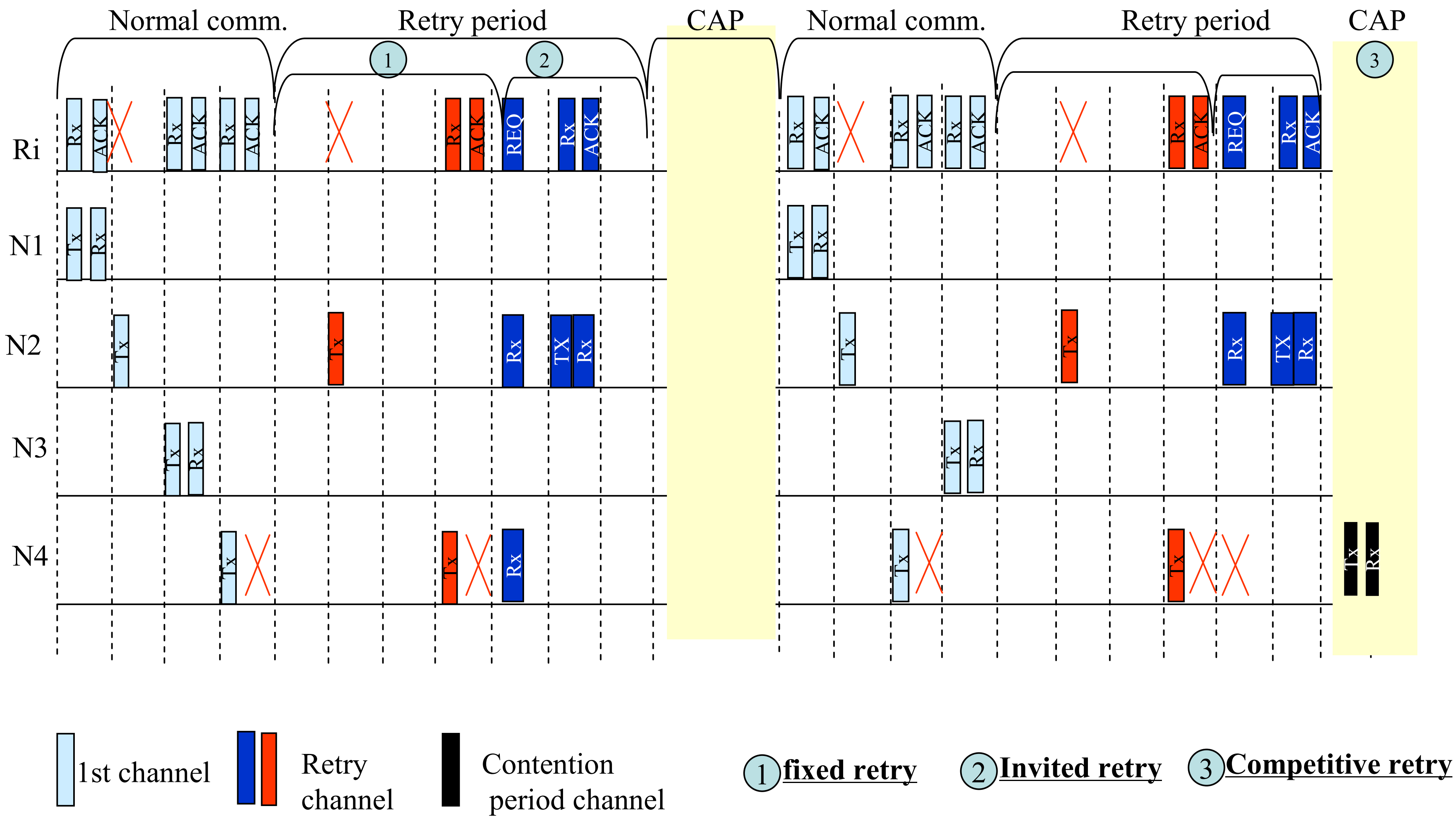
Channel statistics(cont.)

conclusion

■ The packet loss rate over time is relatively stable, especially in the channels with good channel condition or extremely bad channel condition. In another word, for the channel at good communication condition or extremely bad communication condition, the variation of packet loss rate is small.
■There are channel correlations among some channels in terms of the packet loss rate over time.

■The channel features above imply that the channel variation is not random like white noise, and the pre-knowledge does exist. In addition, the pre-knowledge is consistent in the different environments.
■ It indicate that some kind technology of channel condition detection, such as packet loss rate based detection, LQI based detection, can be used to implement adaptive frequency diversity, which will be more efficient than blind frequency diversity.

TDMA+AFD in the Intra-cluster periods



TDMA+AFD in the Intra-cluster periods (cont.)

Algorithm

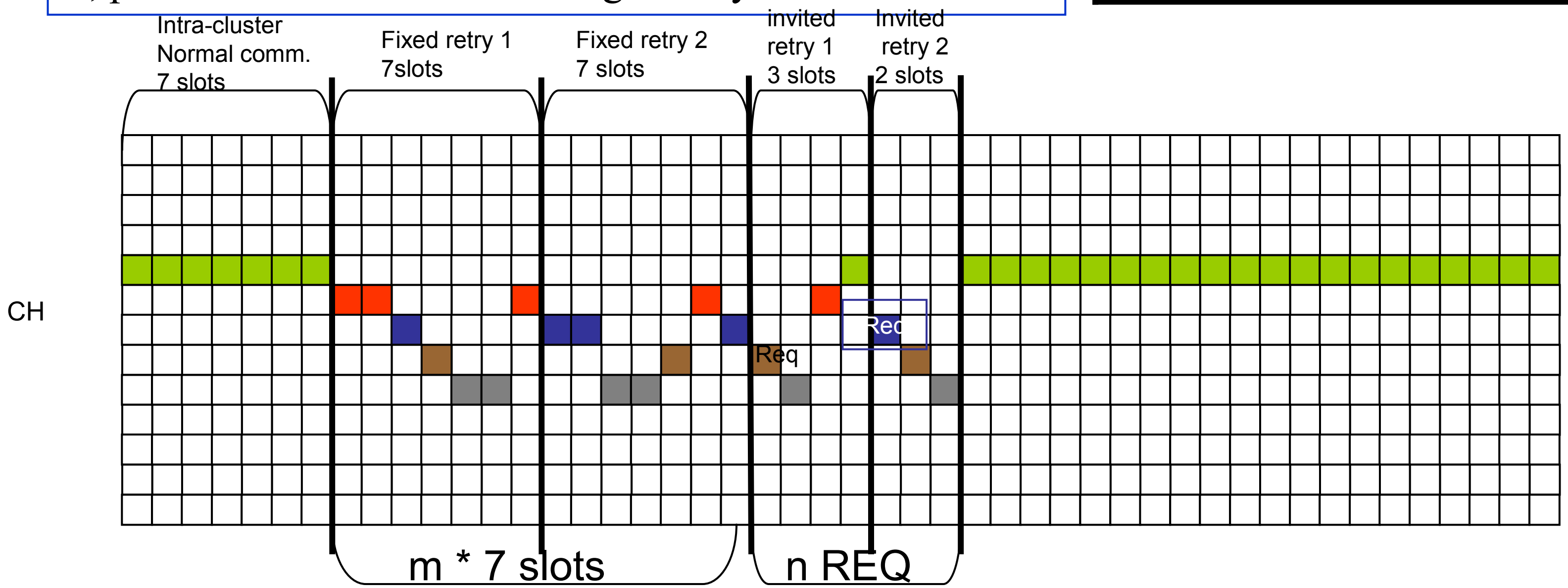
1. A node have k slots, k = m +n +1, m represent fixed retry, n represent invited retry.
2. The communication rules are as follows:
   1. Node employs ch_i to communicate in the first slot
   2. If the first communication fails, retry at m fixed allocated slots : for the devices who didn't receive ACK, they resend packet at its own fixed retry slot;
   3. If the communication failed in the m fixed retry slots, the device will sleep until the REQ slot. While waking up, the device will listen to the REQ broadcast from the cluster-head. The broadcast from cluster-head has the status of the communications on each link, success or fail. For the link on which communication failed, a timeslot is assigned in the broadcast message.
   4. On invited retry period, if cluster-head has received the data but the device lost ACK, the device will know the its package has been received successfully, thus, will not retry again. Otherwise, the device transmits packets in the assigned time slot.
   5. After the device retry, it changes back to the former channel.
   6. If the device retry failed or not received REQ, it can retry during the next CAP.
   7. Node will detect channel condition using packet loss rate, LQI, RSSI etc. to make an evaluation on main channel ch_i and other retry channels, denote as Π, if Π goes beyond the threshold ,cluster head will notice the device to change to a new channel in the manager period, channel is allocated by system manager .

TDMA+AFD in the Intra-cluster periods (cont.)

1, channel in normal communication (we called main channel) and retry channel is allocated by system manager to cluster–head based on the information about channel conditions
2, cluster-head decide to allocate the <slot-channel > to its nodes.
3, The best channel, detected by cluster-head and sensor nodes, is used for normal transmitting
4, parameters m and n are configured by cluster-head

Node 1 channel

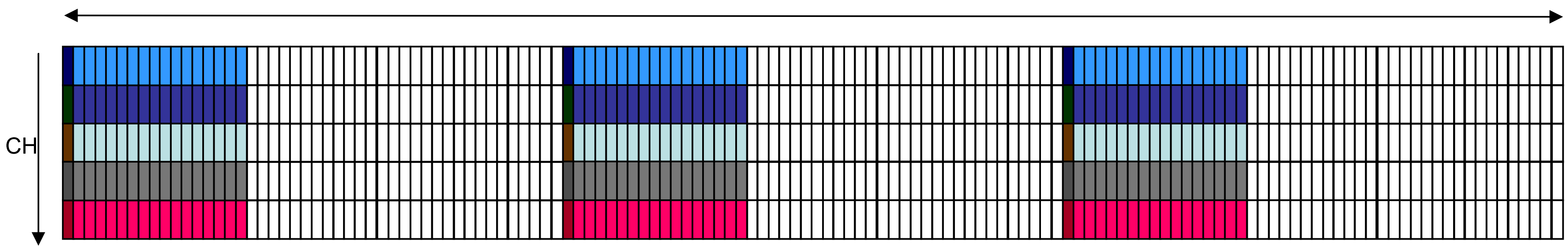
slot	channel	
1	5	normal
8	6	Retry 1
15	7	Retry 2
22	8	REQ
26	7	REQ



TDMA+AFD in the Intra-cluster periods (cont.)

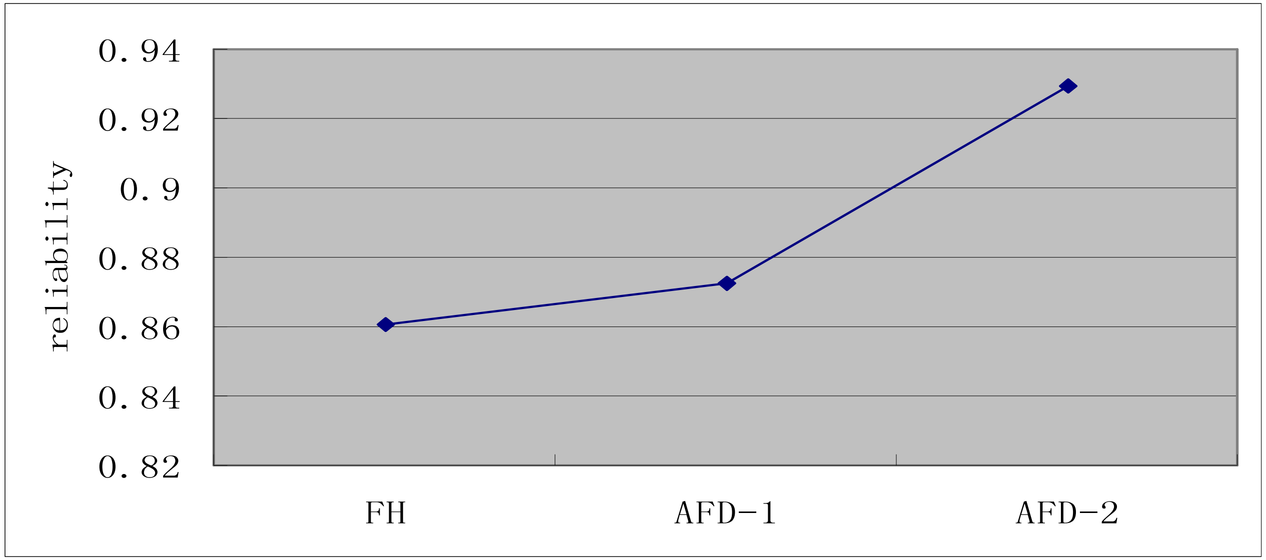
Channel condition detection:

- Each node or cluster-head detect channel by packet loss rate , LQI, or RSSI, and predict channel variation to pre-change current channel when channel becomes bad.
- Current used channels, include main channel for normal transmitting, fixed/invited retry channels, are detected by nodes and cluster-head when they use those channels.
- To detect no-used channels and channels that are dropped by the cluster-head and node, we will change CAP+CFP channels periodically to collect packet loss rate , LQI, or RSSI.



TDMA+AFD in the Intra-cluster periods (cont.)

AFD/HF reliability simulation



FH using all 16 channels
AFD-1 using 3 channel 12, 11, 1
AFD-2 using 2 channel 12, 1
No retry in all of them
channel condition see page 7
packet loss rate threshold for change channel : 30%
Packet loss rate statistic time: 50 transmissions

Summary

1. The packet loss rate over time is relatively stable, especially in the channels with good channel condition or extremely bad channel condition
2. Frequency diversity is a effective way to increase reliability, while it is based on choosing good channel other than blind choosing .

Conclusion from 0619 & 0620

1. Mesh+Star topology
2. Extended superframe
3. CSMA/TDMA+FDMA during active period
4. TDMA+FH/**AFD** during scheduled period with two stage allocation
5. **AFD**: using good channels only with channel detection