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

Submission Title: [Samsung MAC proposal – Part 1: A power efficient MAC for BAN]
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Re: [TG6 Call For Proposals, IEEE P802.15-08-0829-01-0006, 4th December, 2008]

Abstract: A complete MAC proposal addressing the functional requirements of implant and on-body communications. Part 1 includes the Channel Access Scheme, Single MAC Design aspects wherein Part 2 includes the Co-existence, Network management and Security related aspects

Purpose: To trigger discussion and initiate merger with other group members of TG6.

Topics covered by Samsung MAC Proposal

- Part 1 covers:
  - Channel access mechanism for On-body communication
  - Channel access mechanism for Implant communication
  - Emergency data handling
  - Single MAC design
- Part 2 covers:
  - Wakeup mechanism
  - Coexistence
  - Network management
  - Security

Part 1 - Outline

- **TG6 MAC functional requiremnts**
- **Channel access mechanism for On-body communication**
  - Traffic types and requirements
  - Design approach
  - Rationale behind selection of Polling based Channel Access Mechanism
  - Frame design
  - Polling mechanism for different type of traffic
  - Integrated frame structure
  - Simulation results
- **Channel access mechanism for Implant communication**
  - Overview
  - Channel Access Mechanism Design
  - Emergency Data Transfer
  - Implant Co-existence
  - Simulation Results
- **Single MAC design**
  - Design Approach
  - Single MAC Solution
  - Piconet modes and device classifier
  - Simulation results
- **Comparison criteria and TRD coverage**
- **Conclusion**

TG6 MAC functional requirements

1. MAC transparency – Support of multiple PHYs
2. Topology supported
3. Support of scalable data rate
4. Support of number of devices
5. Medical application traffic latency (< 125 ms)
6. Non-medical application traffic latency (< 250 ms)
7. Non-medical application traffic packet delay variation (< 50 ms)
8. Low power consumption
9. Availability of 99%
10. Capability of providing fast (<1 sec) channel access in emergency situations (alarm messages)
11. Coexistence of 10 BANs in the proposed implant communication band
12. Coexistence of 10 BANs in the proposed on-body communication band
13. Time to associate a node to BAN
14. Support of security

Channel Access Mechanism for On-body Communication

- Traffic types and requirements
- Design approach
- Rationale behind selection of Polling based Channel Access Mechanism
- Frame design
- Polling mechanism for different type of traffic
- Integrated frame structure
- Simulation results

Traffic types and requirements

Class	Description	Performance Requirements	Example

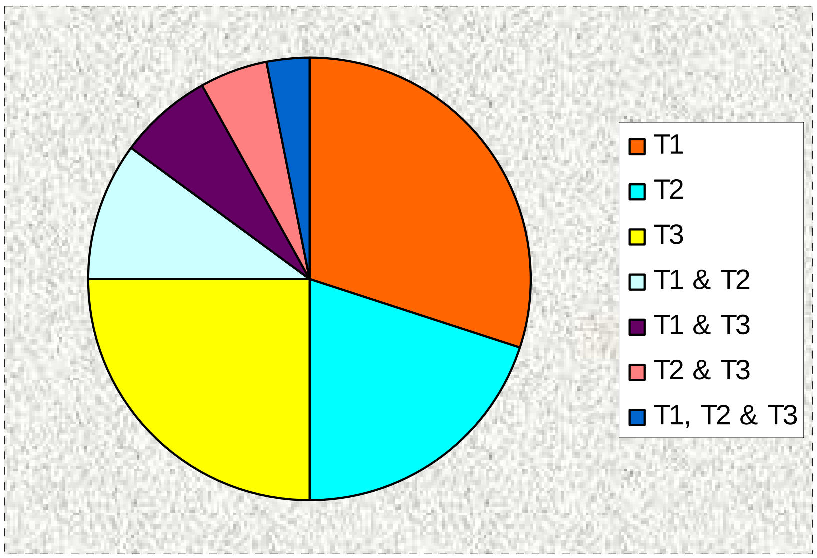
T_1	CBR low data rate traffic	• Low power consumption
		• Packet delay required by the application, e.g.
		    • 125 ms for patient monitoring
		    • 250 ms for Gaming
		• Support of large number of devices
			• Patient Monitoring
			• ECG
			• Fitness Applications
			• Interactive Gaming

T_2	CBR high data rate traffic	• Low power consumption • Packet delay	• EMG • Uncompressed Audio
T_3	VBR traffic	• Delay and Packet Delay Variation • Maximization of bandwidth utilization • Power efficiency is optional	• Real-time Multimedia Streaming

Design Approach

Objective: To design a channel access mechanism which can meet the performance requirements of all three class of traffics.

Traffic Scenarios:



Prioritization Order and Scheme:

- Order: $T_1 \rightarrow T_2 \rightarrow T_3$
- Scheduling of low priority traffic should not affect the performance of high priority traffic

Example:

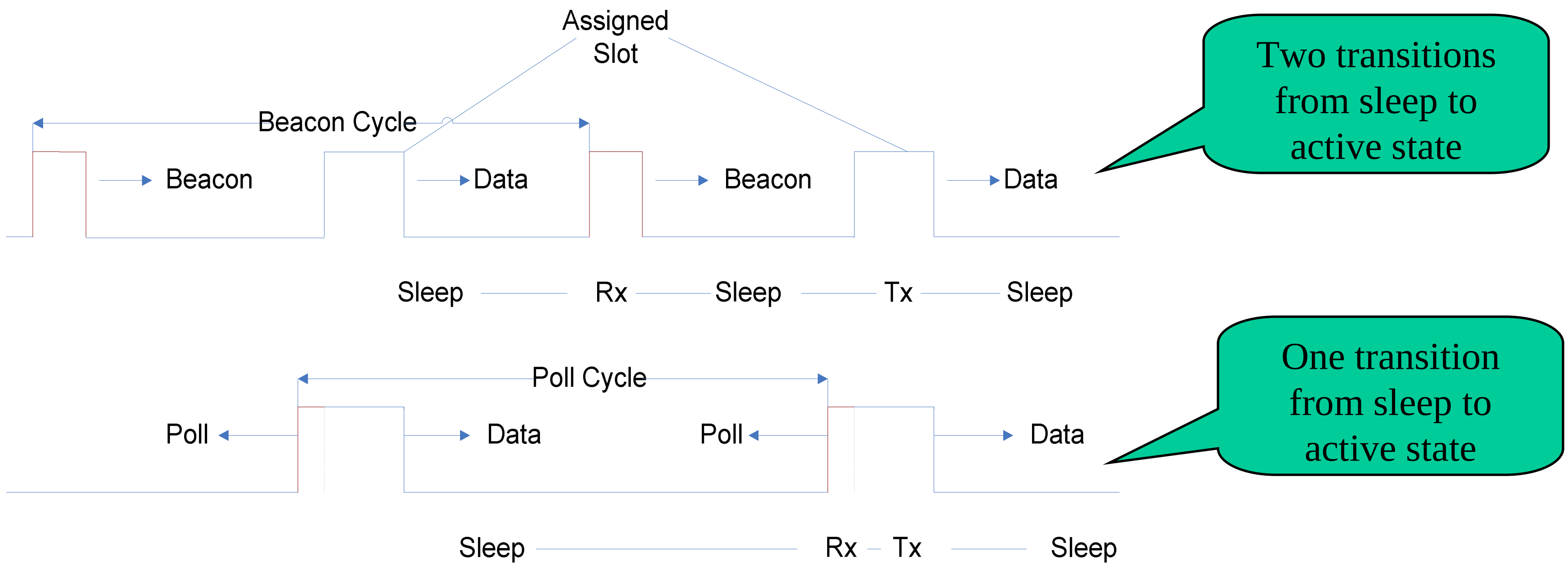
- $\longrightarrow$ T_1, T_2 and T_3
  - T_1 and T_2 performance should be close to standalone
  - Presence of T_3 should not affect the performance of T_1 and T_2
  - With above constraints, try to maximize T_3 performance

Rationale behind Polling based Mechanism

Polling based channel access mechanism is preferred with proposed design approach, due to following reasons:

- Centralized Control
    - Suitable for star topology
- Contention free channel access mechanism
- Slot level synchronization is not required for data transmission
    - Hard to achieve slot level synchronization at higher (10 Mbps) data rates
- Variable slot design possible
    - Bandwidth efficient (required for T3 traffic)
- Facilitates independent sleep/wakeup schedule
    - Power efficient
- Facilitates Single MAC design

Broadcast message (Beacon) Vs Unicast message (Poll)



- **Power consumption**
  - Beacon size is larger than poll size
  - Energy spent in transition is significant at high frequency
- **Reliability**
  - A Unicast Poll Message has lesser reliability requirement than the Broadcast Message (e.g. Beacon)

Overview of Frame Design for On-body communication

Polling Period	EOP	Contention Period
• CBR low data rate traffic (T_1) • CBR high data rate traffic (T_2) • VBR traffic (T_3)	• Broadcast message, Indicates the end of poll period and the beginning of Contention Period • Contains length information of Contention Period and Piconet related information (Mode of coordinator, Capability of Piconet, etc)	• Network management traffic (e.g. Association and disassociation) • Best effort traffic (e.g. Medical Log-file transfer)

Frame Design for On-body communication

Design criterions for Frame cycle time (F_c)

(i) $F_c \leq d_{\min}$

(ii) $F_c \geq (\sum_{i=1}^{n} P_i + S_i) / R + 2n * IFS$

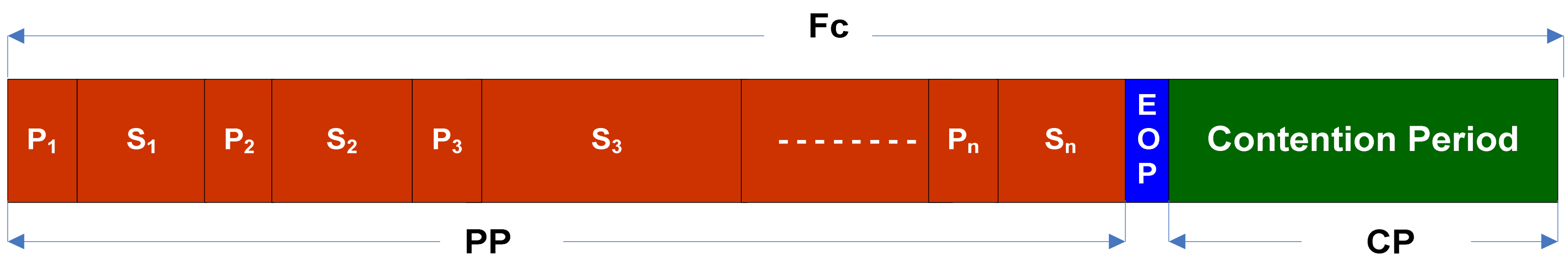
(iii) F_c is fixed

- Number of devices = n
- S_i is the allocated slot time for i[th] device
- $d_{\min}$ is the minimum delay requirement among the applications
- R is the bit rate
- P_i is the Poll message for i[th] device, P_1 = - - - = P_n

- Fixed F_c allows efficient duty cycling at the devices
- minCP is the minimum contention period required for network management (e.g. Association)
- Polling Period is variable and bounded, PP ≤ F_c – minCP

Polling mechanism for T_1

- A device is polled with period F_c
- **When Polled, device has at most one packet of size < MTU to transmit**
- Arrival rate ≤ A_m, Where A_m is maximum arrival rate for T1



Power saving:

- F_c is fixed, S_i is fixed → Poll time of i^{th} device is fixed
- Device can go to sleep after data transmission and wakeup before the poll time
- Very low data rate devices may perform packet aggregation

Delay:

- Packet latency is bounded by F_c, if data not in error

Bandwidth Efficiency

- Variable allocated slot duration (Si) for different arrival rates

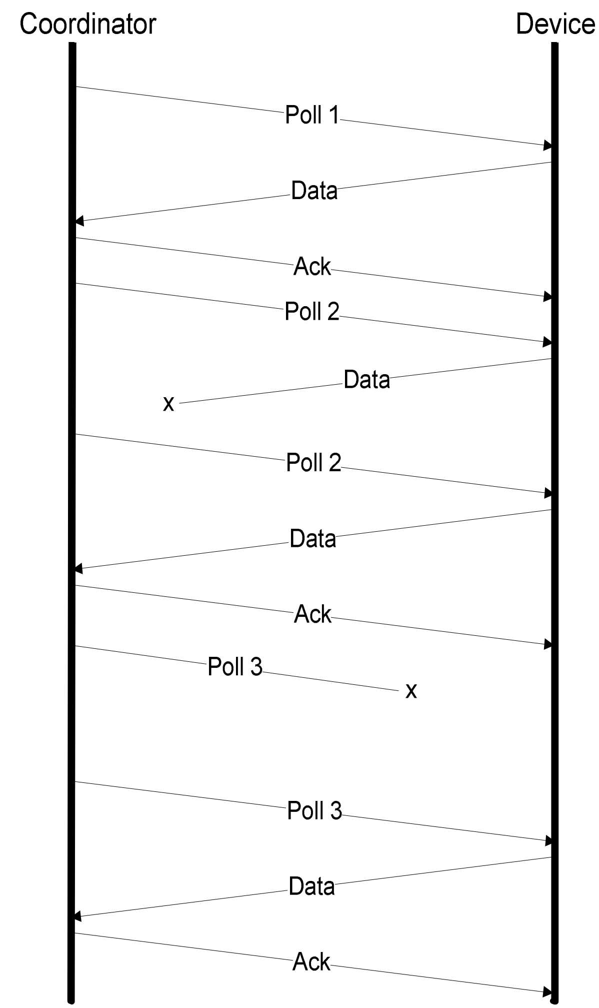
Polling mechanism for T1 with error

Reliability

- Retransmission is handled in the same Frame Cycle
  - Poll period may extend up to minCP
- Delayed poll message due to error lead to idle listening and overhearing at device

Error recovery mechanism:

- Retransmission mechanism (Data or poll loss)
  - Coordinator transmits the poll message again
  - Collision between data and poll message avoided
- ACK loss
  - Device goes to sleep on receiving poll of next device
- Immediate ACK helps in saving power when packet transmission is successful before allocated slot duration



Simulation Details for T1

Application	Arrival rate/devices	Number of devices	Allocated slot time (S_i) per device (ms)
ECG	4 Kbps	20	0.582
Vital Signal Monitoring	4 Kbps	20	1.164
EEG	8 Kbps	20	0.582
Interactive Gaming	4 Kbps	40	0.582
Fitness	4 Kbps	20	0.582

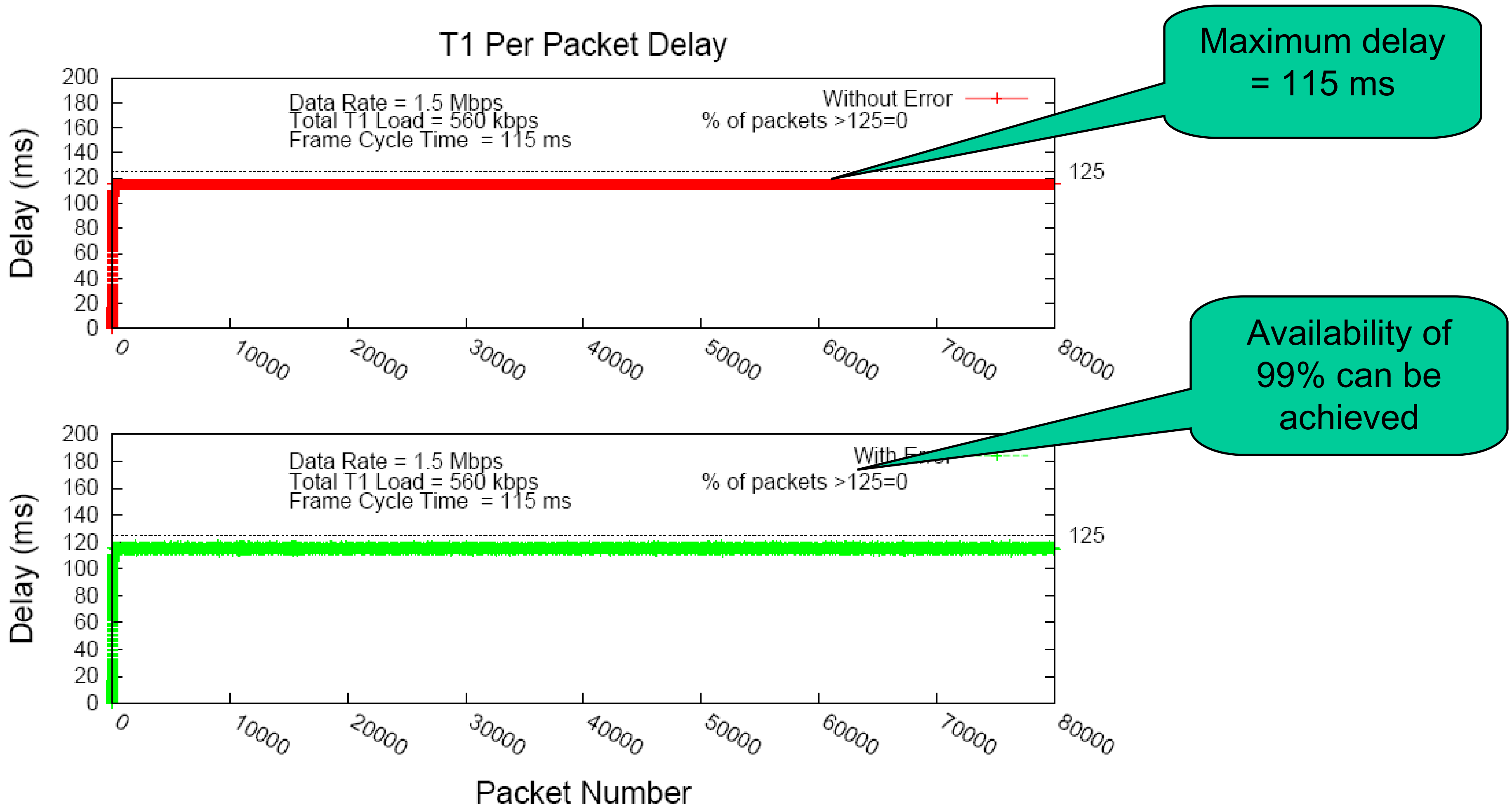
Simulation Run	100 sec
Data rate	1.5 Mbps
Total load	560 kbps
Frame cycle	115 ms
IFS	15 µs
Poll size	15 bytes
ACK size	15 bytes

Delay: Queuing delay + Channel access delay + Transmission delay

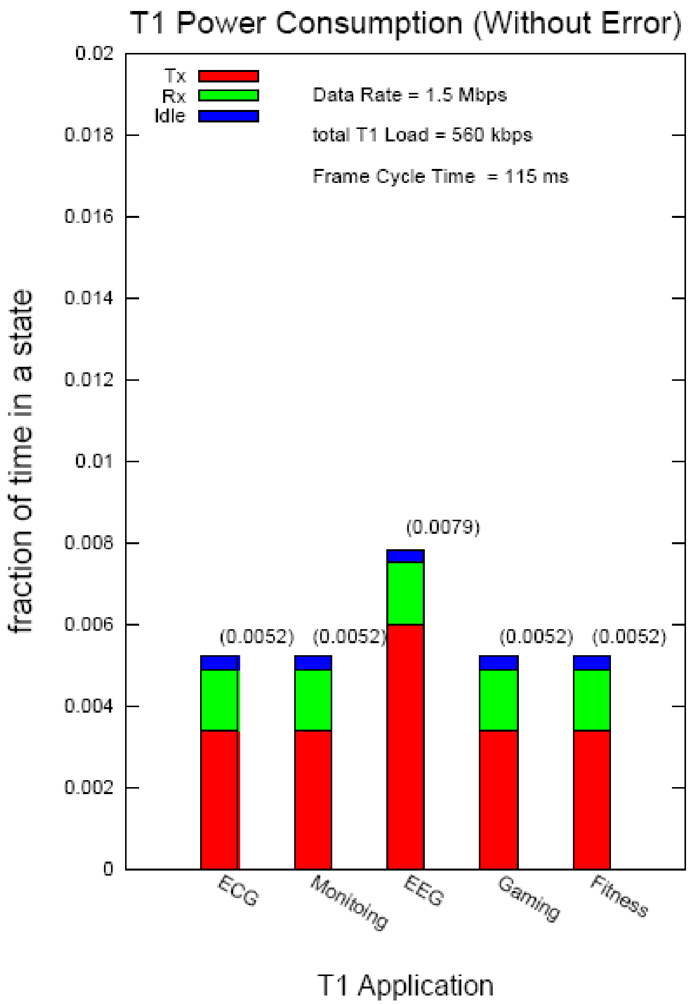
Power consumption: Total power consumption due to radio can be calculated from the time spent at different states

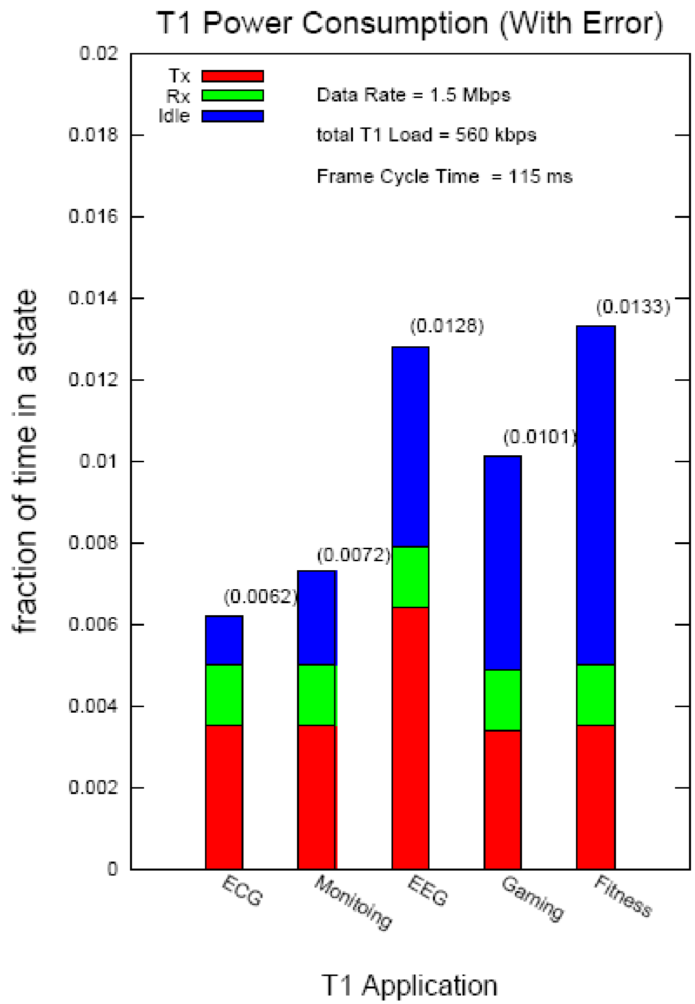
C++ based simulation framework is used to obtain all the simulation results

Simulation results of T1 - Delay



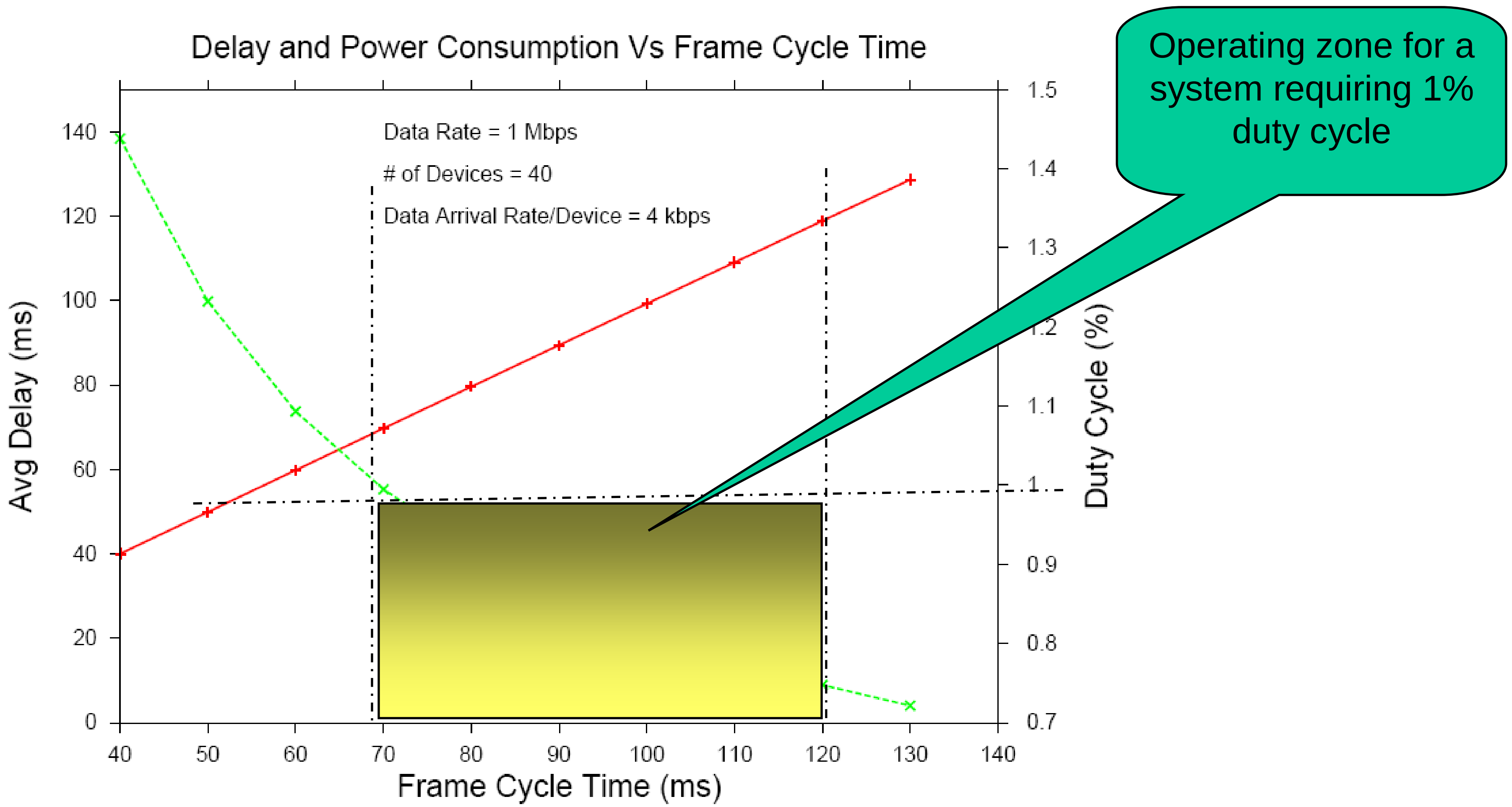
Simulation results of T1 - Power consumption



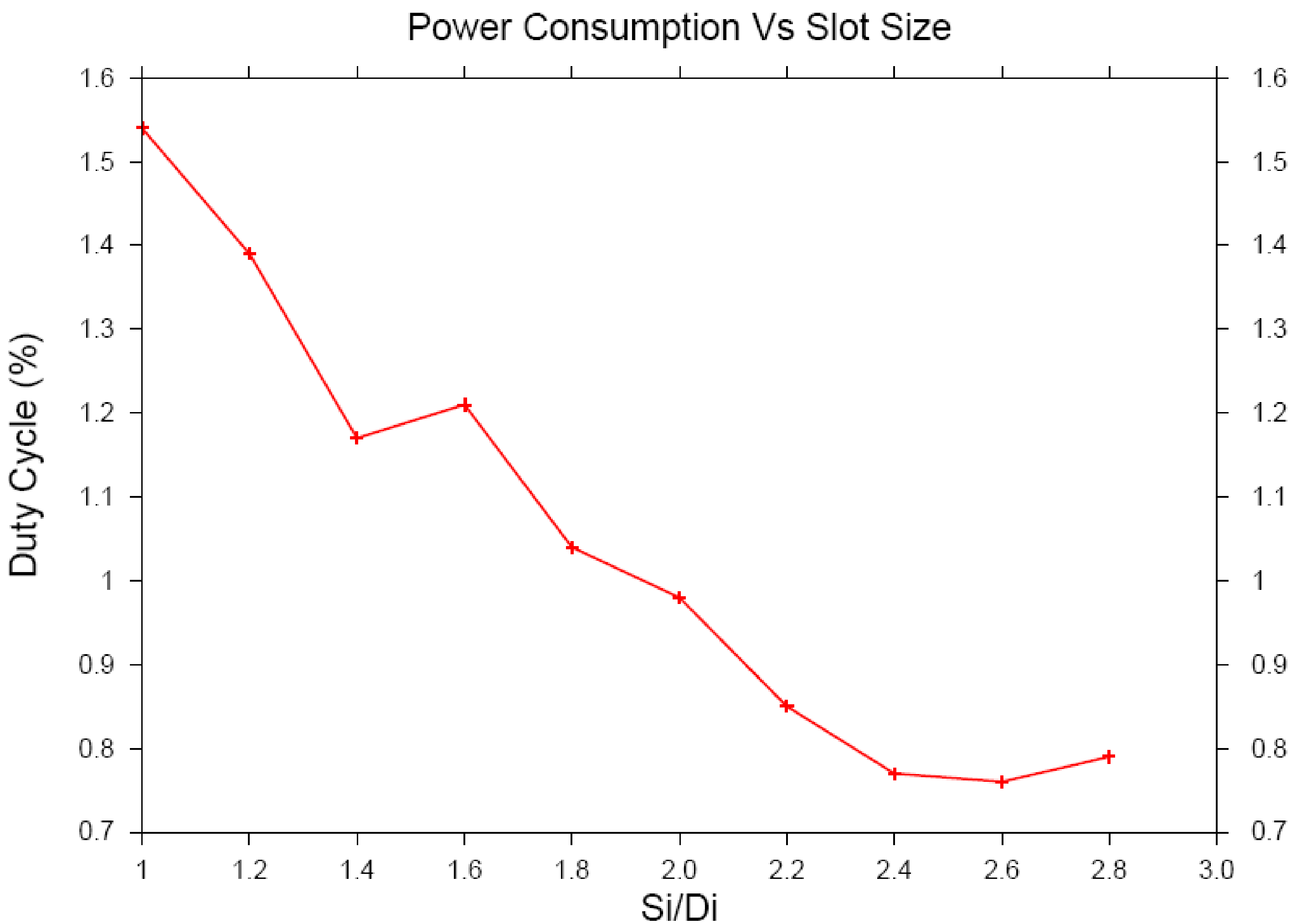


- Without error, duty cycle of less than 1% achieved for all exemplary applications
- Devices with higher arrival rate (EEG, 8 Kbps) have high power consumption
- Device polled later in polling sequence experience more idle listening in case of error

Selection of F_c to meet Delay and Power requirement

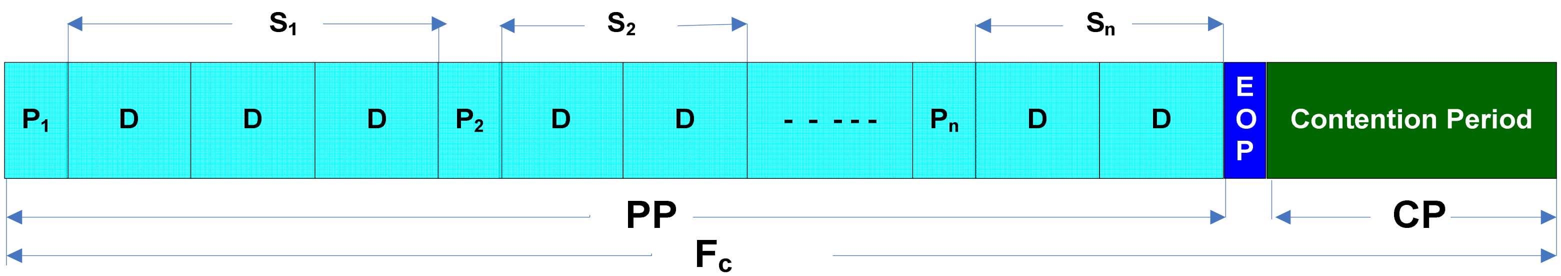


Selection of S_i to meet Power requirement



Polling mechanism for T2

- When Polled, device may have more than one packet of size MTU to transmit
- Allocated slot time Si, is to accommodate multiple packet transmission of size MTU
- Arrival rate > A_m, Where A_m is minimum arrival rate for T2
- Si is calculated based on packet arrival rate



Power saving:
- F_c is fixed, S_i is fixed → Poll time of i^{th} device is fixed
- Device can go to sleep after data transmission and wakeup before the poll time

Delay:
- Packet latency is bounded by F_c, if data not in error

Bandwidth Efficiency
- Single Poll for multiple Packets

Polling mechanism for T2 with error

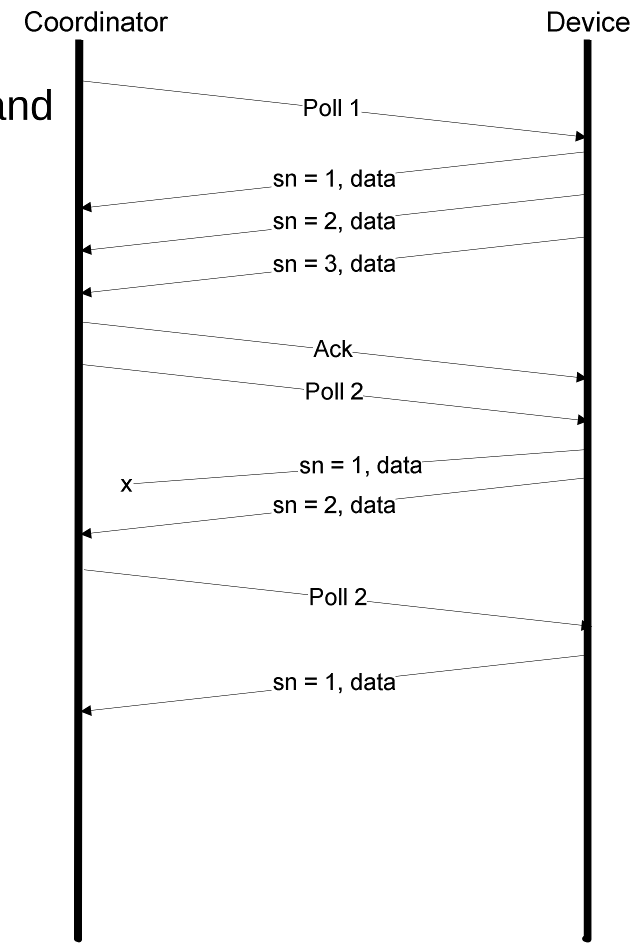
Reliability

- Retransmission is handled in the same Fc
- Delayed poll message due error lead to idle listening and overhearing at device

Error recovery mechanism:

- All packets are successful
    - Block ACK is transmitted by the coordinator
- Retransmission mechanism (Poll or Data loss)
    - Coordinator transmits the poll message again
    - Collision between data and poll message avoided
- ACK Loss
    - Device goes to sleep mode after receiving poll of next device

• Block ACK helps in saving power and achieves higher bandwidth utilization



Simulation Details for T2

Application	Arrival rate/devices	Number of devices	Allocated slot time (S_i) per device (ms)
EMG	96 Kbps	12	4.8
Audio (CBR)	64 Kbps	10	2.73

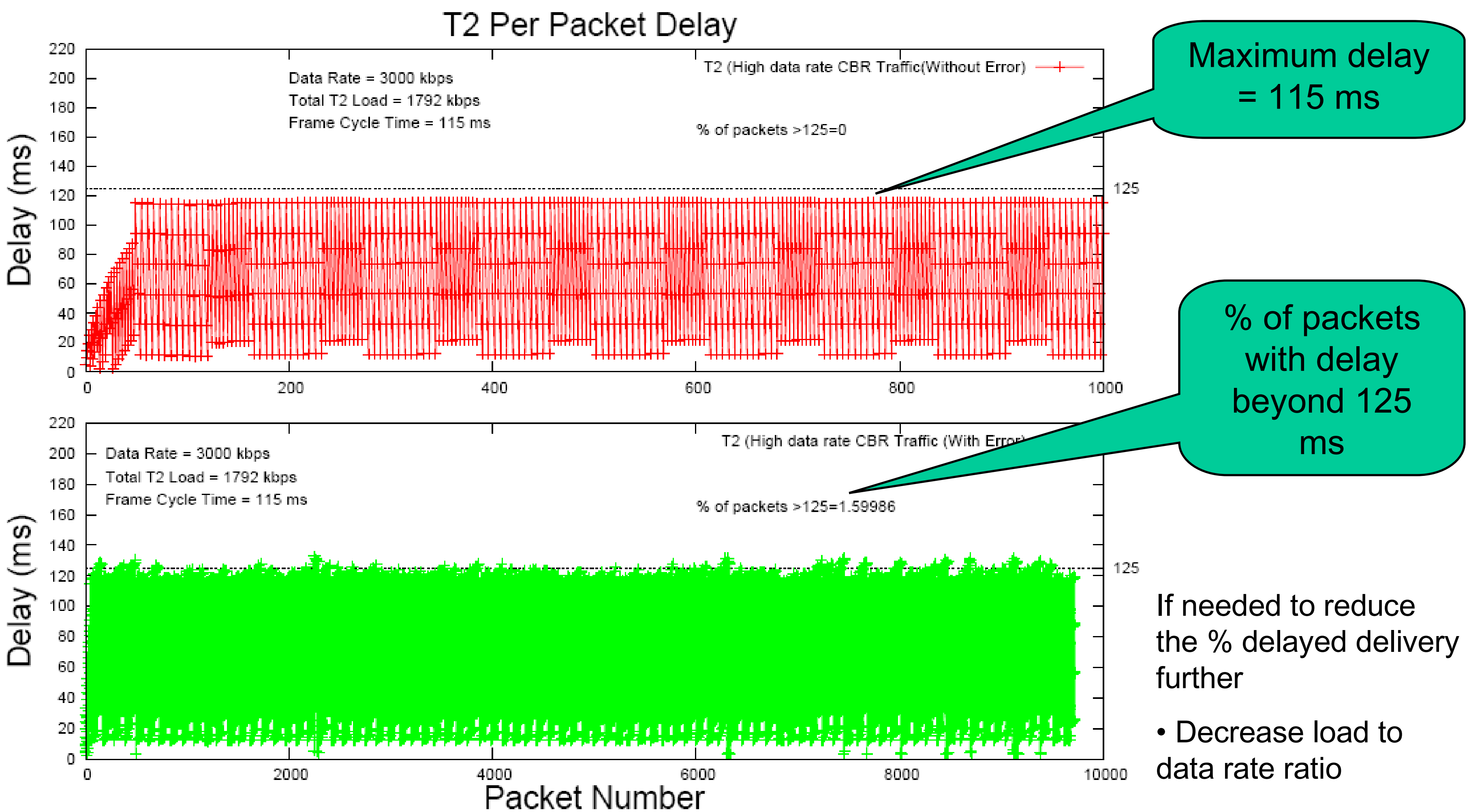
Simulation Run	100 sec
Data rate	3 Mbps
Total load	1792 kbps
Frame cycle	115 ms
IFS	15 µs
Poll size	15 bytes
ACK size	15 bytes

Delay: Queuing delay + Channel access delay + Transmission delay

Power consumption: Total power consumption due to radio can be calculated from the time spent at different states

C++ based simulation framework is used to obtain all the simulation results

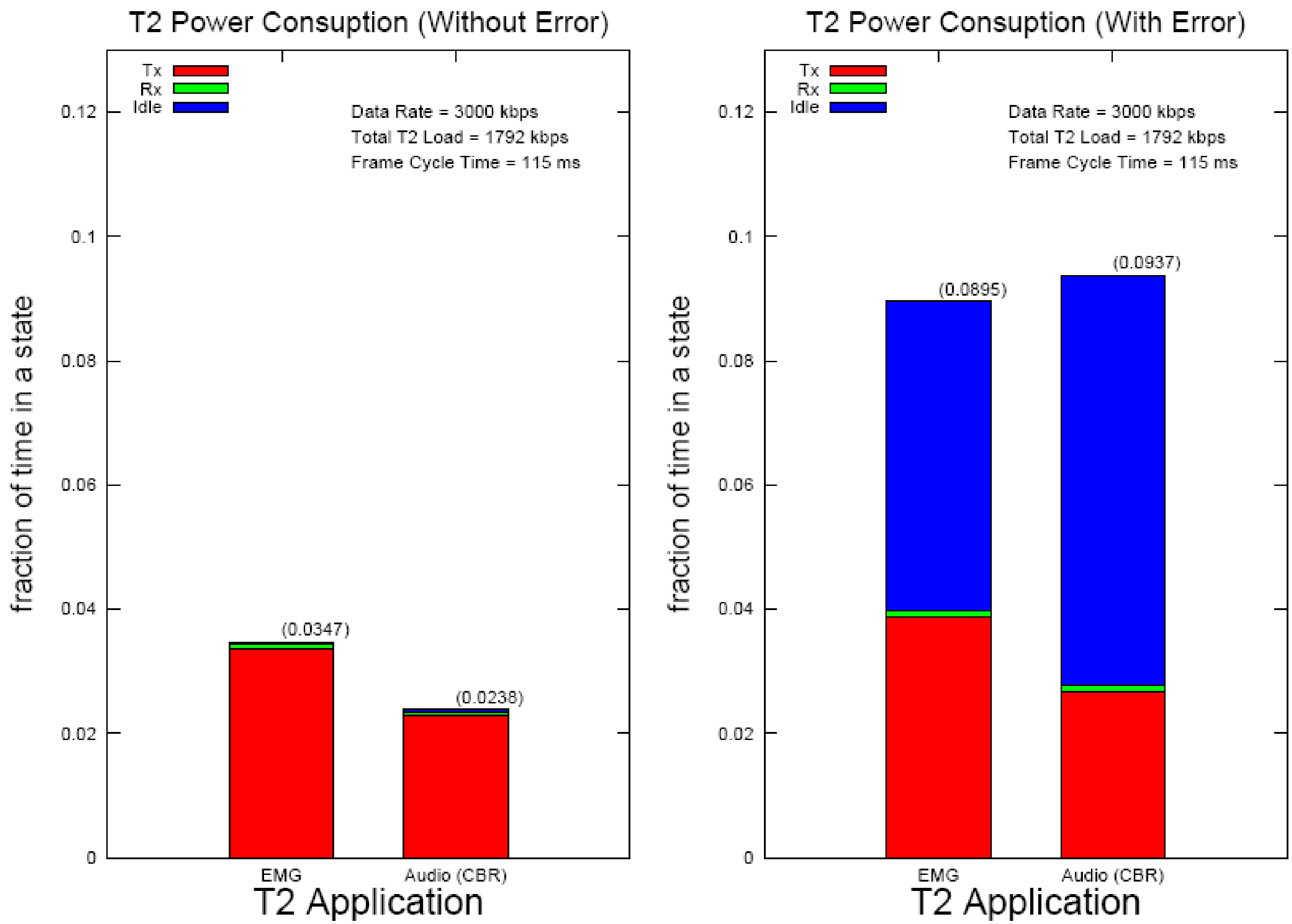
Simulation results of T2 - Delay



If needed to reduce the % delayed delivery further

- Decrease load to data rate ratio

Simulation results of T2 – Power Consumption

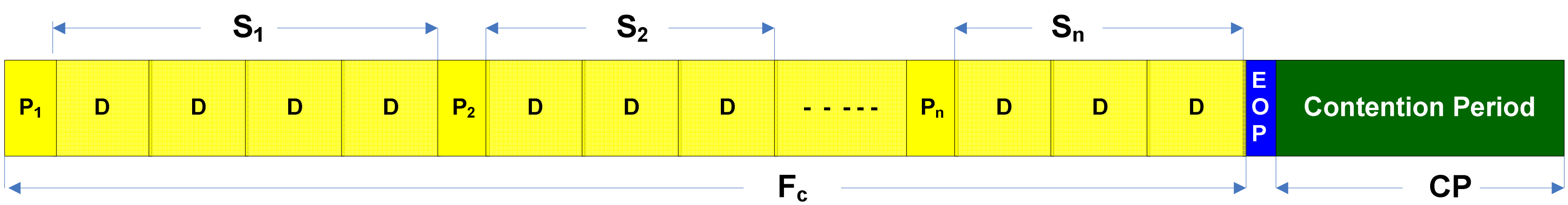


Low Power Consumption Considerations for T1 and T2

1. Fixed F_c facilitates a static sleep/wakeup schedule
2. T1 devices are polled first to save the power
   - T2 data transmission has higher probability of being In error due to larger packet size
3. Power consumption of devices can be reduced by increasing Frame Cycle (F_c) time
4. Idle listening and overhearing can be reduced by allocating larger slot duration than required by the application's packet arrival rate
   - This allows retransmission of lost packets to happen within allocated slot duration, thereby do not effect the poll time of devices comes later in the polling sequence
5. Immediate ACK helps in saving power when packet transmission is successful before allocated slot duration
6. Inside T1 or T2 traffic types, higher power constraint devices can be polled ahead of lesser power constraint devices

Polling mechanism for T3

- ***F_c* is variable, Polling time is not fixed**
- The device transmits all the packets in the buffer that were stored, when polled
- One data packet (D) is of MTU size



Power

- Power is not a major constraint T3 applications (devices are active all the time)

Delay:

- No fixed F_c , delay is variable

Bandwidth Efficiency:

- Dynamic slot allocation achieves higher throughput

Simulation Details for T3

Movie Name	Compression ratio	Mean frame size (bytes)	Peak/Mean (Packet size)	Mean (Kbps)	Peak/Mean (Data rate)
Star Wars	27.62	1400	6.81	280	1.9
Star Trek	23.11	1600	7.59	330	2.5
Silence of the Lambs	13.22	2900	7.73	580	4.4
Mr. Bean	13.06	2900	5.24	580	3.1

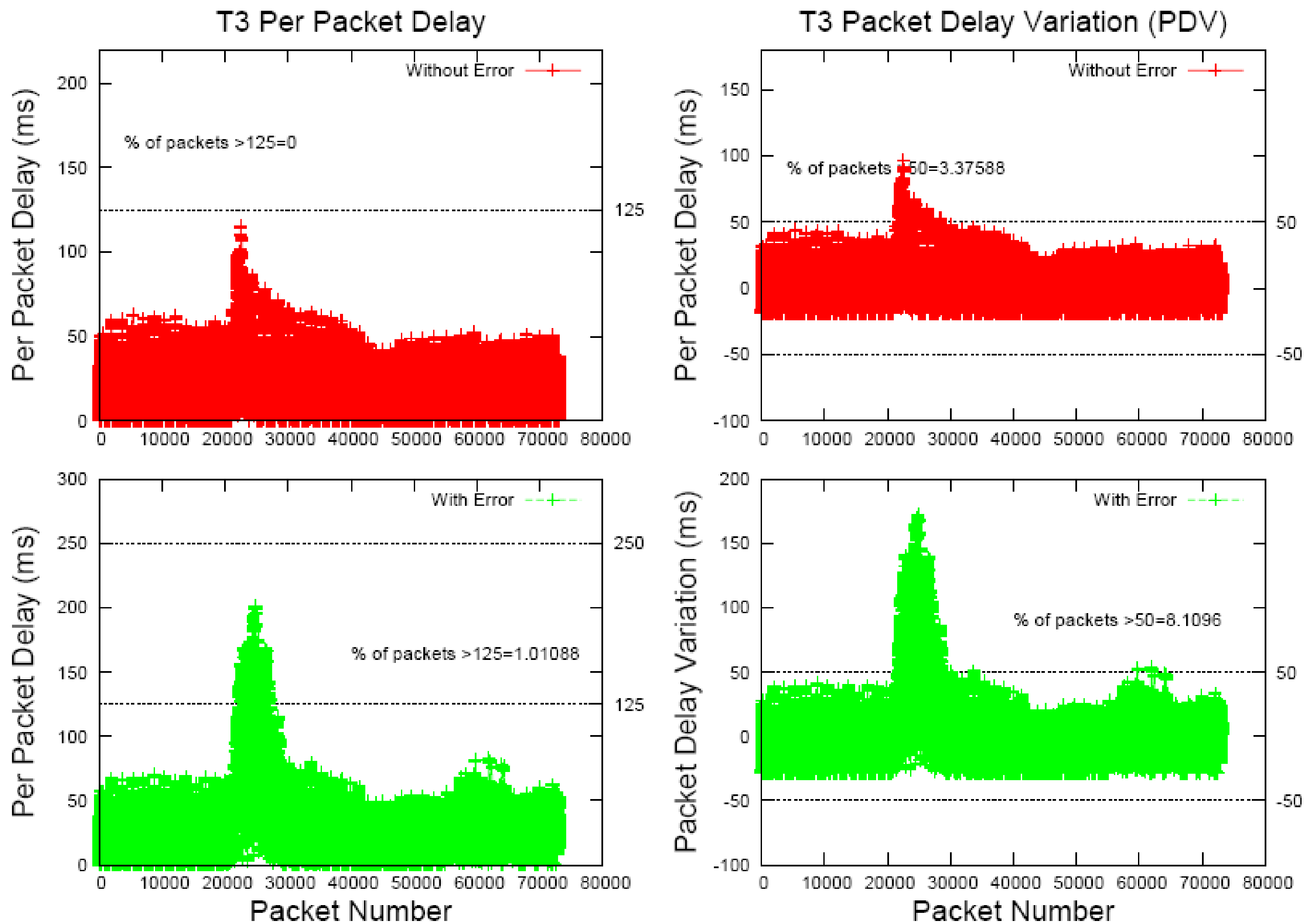
Data rate	10 Mbps
Frame cycle	115 ms
IFS	15 µs
Poll size	15 bytes
ACK size	15 bytes

MPEG-4 movie traces are used for traffic generation [1].

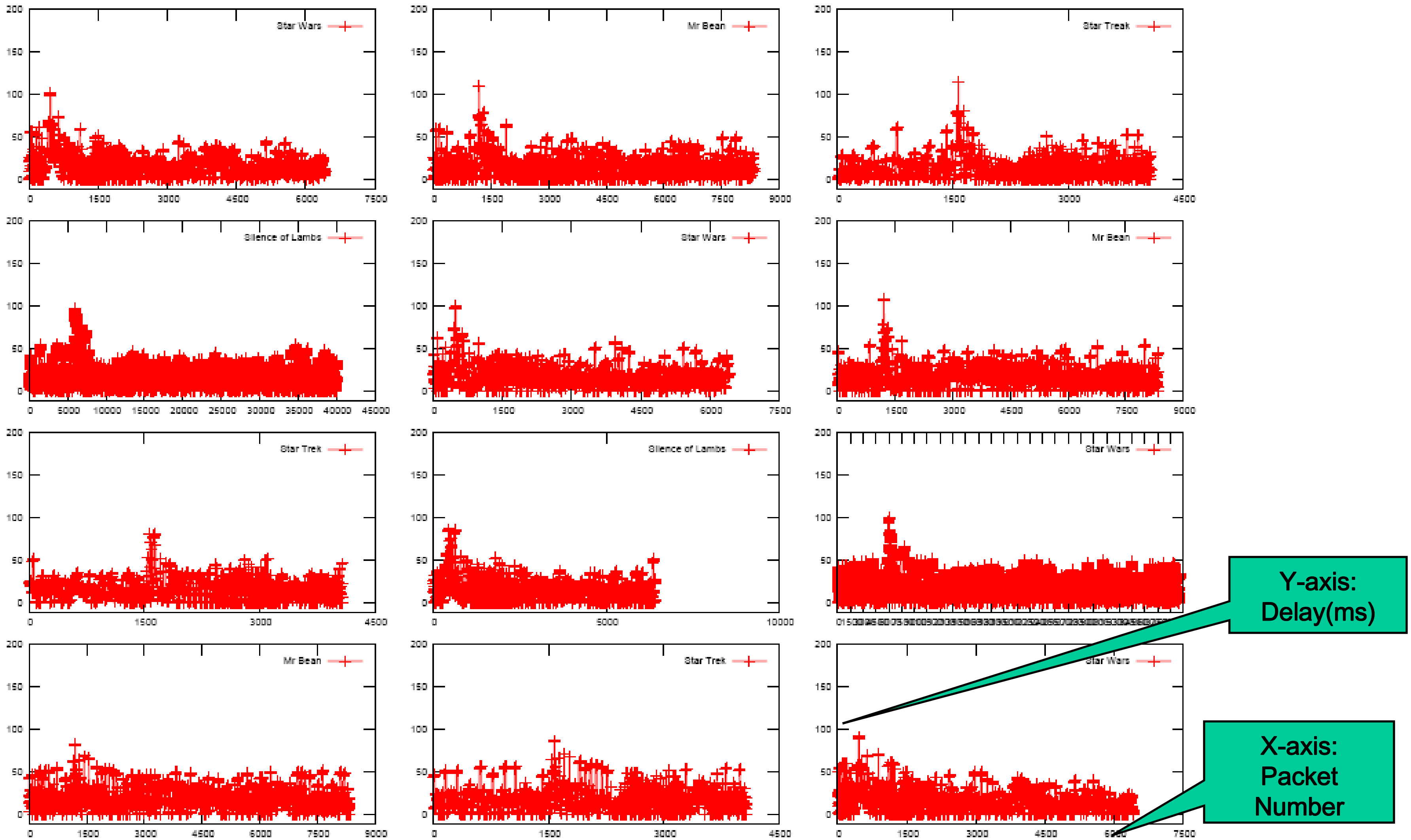
Delay: Queuing delay + Channel access delay + Transmission delay

Packet delay variation: Deviation to the reference value. Reference value is the mean packet delay.

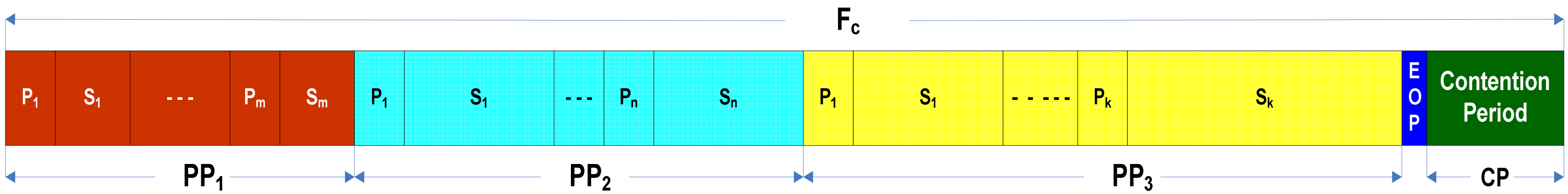
Simulation results of T3 - Delay



Simulation results of T3 – Delay distribution per device



Integrated Frame Structure



Description:

1. T_1 has highest priority
   - Bandwidth is reserved to support required applications in T_1, whenever T_1 coexist with other class of traffic
2. T_2 has higher priority than T_3
   - Admission of a new T_2 application may affect T_3 application (Delay, PDV)
   - Admission of new T_3 application does not affect T_2 application performance
3. Support of T_3 application is maximized while following 1 and 2.

- F_c is fixed, $F_c = PP_1 + PP_2 + PP_3 + CP$
- PP3 may take different value in different frame and bounded, $PP_3 \leq F_c - (PP_1 + PP_2 + minCP)$

Simulation Details for T1, T2 and T3

Application	Arrival rate/devices	Number of devices	Allocated slot time (S_i) per device (ms)
ECG	4 Kbps	20	0.087
Vital Signal Monitoring	4 Kbps	20	0.087
EEG	8 Kbps	20	0.174
Interactive Gaming	4 Kbps	40	0.087
Fitness	4 Kbps	20	0.087
EMG	96 Kbps	96	1.433
Uncompressed Audio	64 Kbps	10	1.024

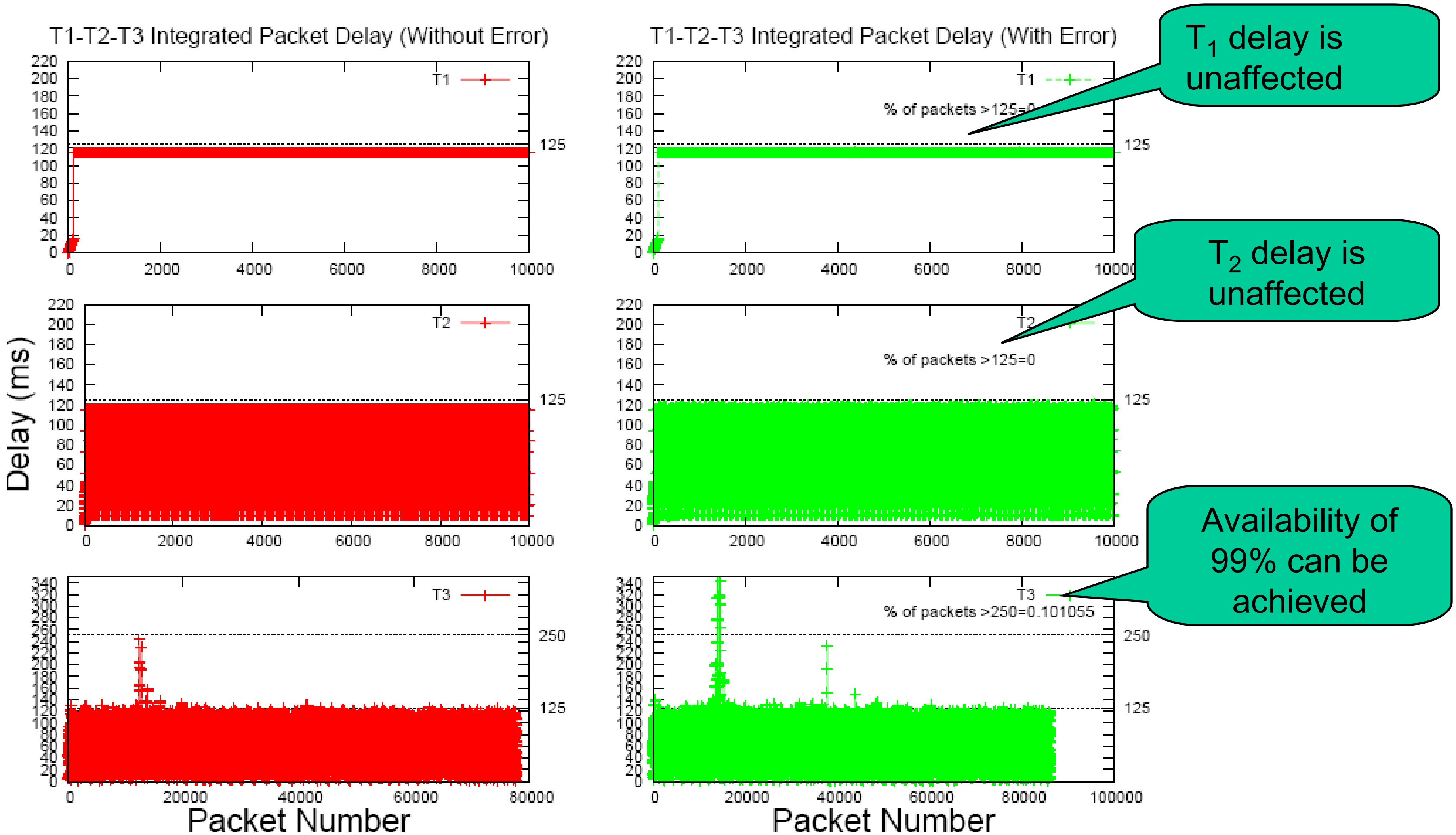
Simulation Run	40 sec
Data rate	10 Mbps
Frame cycle	115 ms
IFS	15 µs
Poll size	15 bytes
ACK size	15 bytes

T3 load: 7 Mpeg traffics

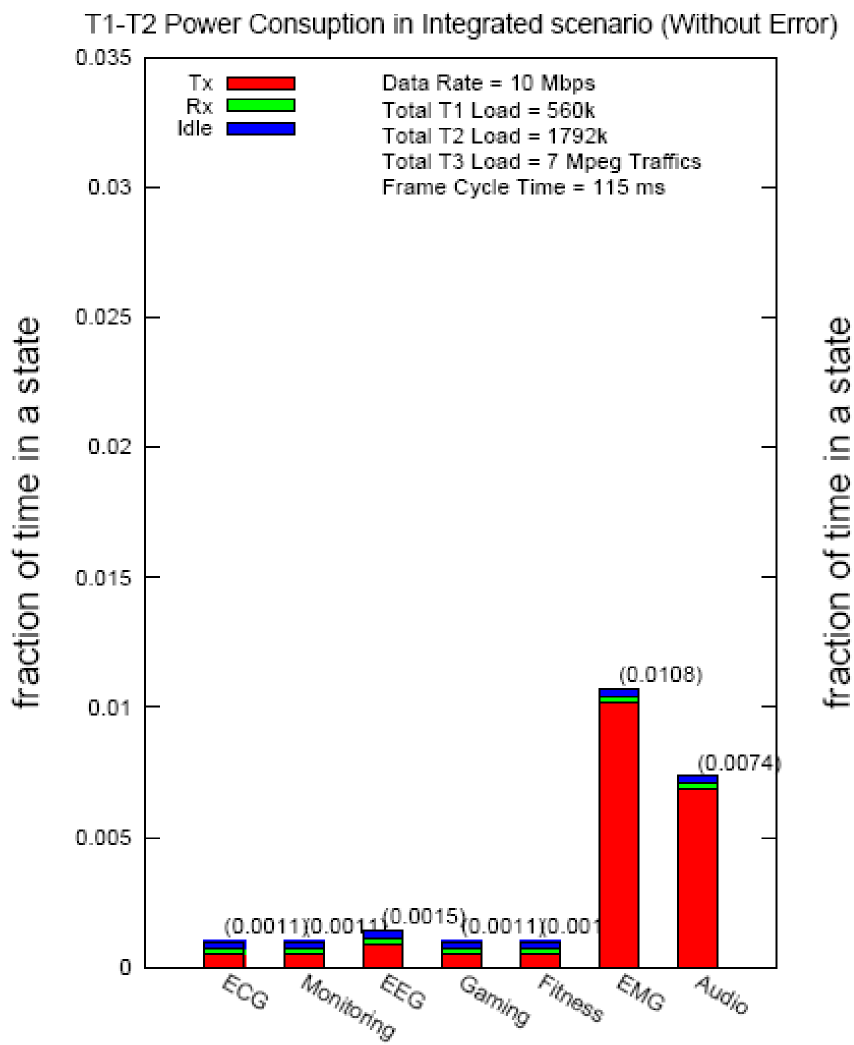
Delay: Queuing delay + Channel access delay + Transmission delay

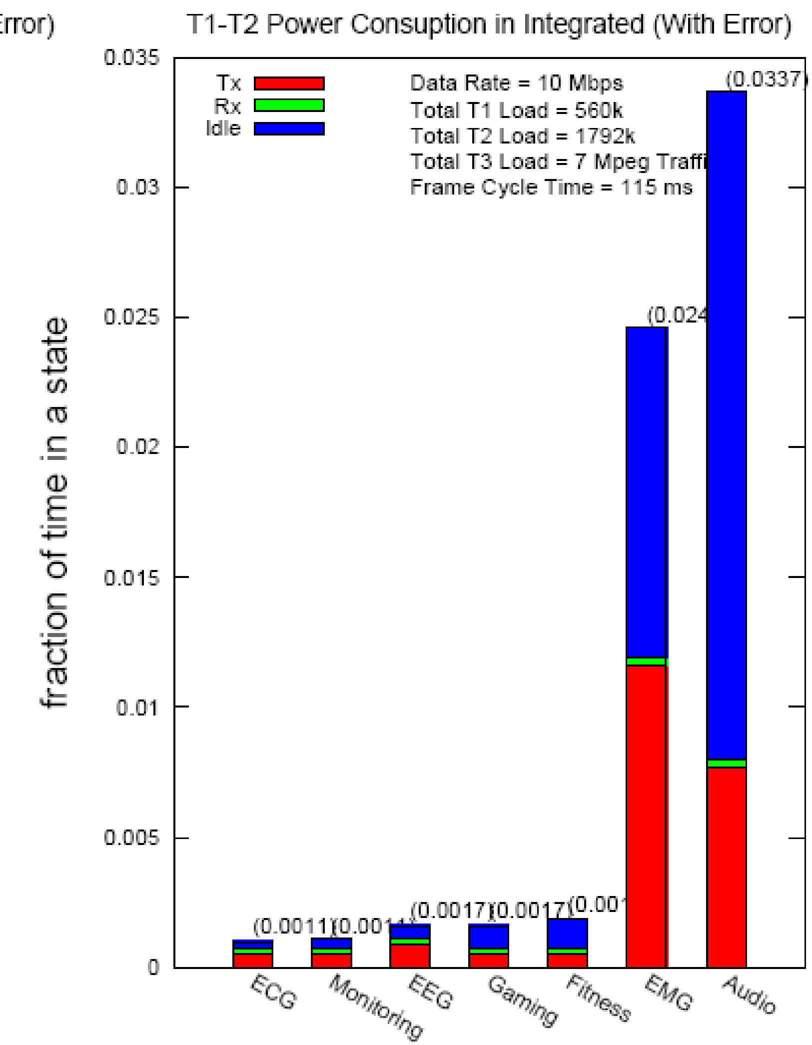
Power consumption: Total power consumption due to radio can be calculated from the time spent at different states

Simulation results of Integrated T1, T2 and T3



Simulation results of Integrated T1, T2 and T3

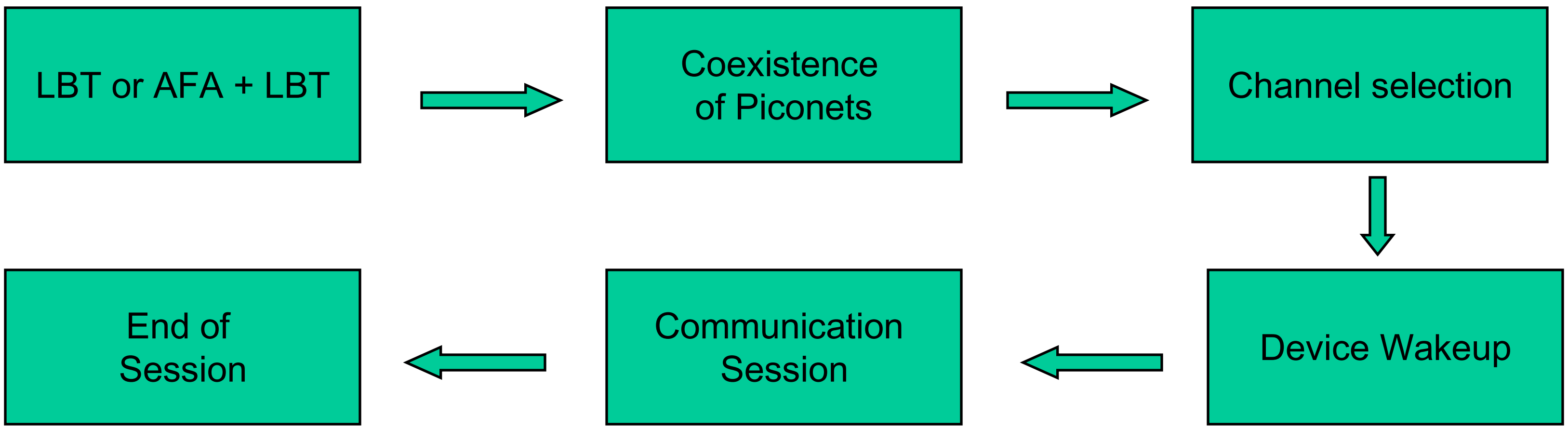




Channel Access Mechanism for Implant Communication

- Overview
- Channel Access Mechanism Design
- Emergency Data Transfer
- Implant Co-existence
- Simulation Results

Implant Communication – Overview



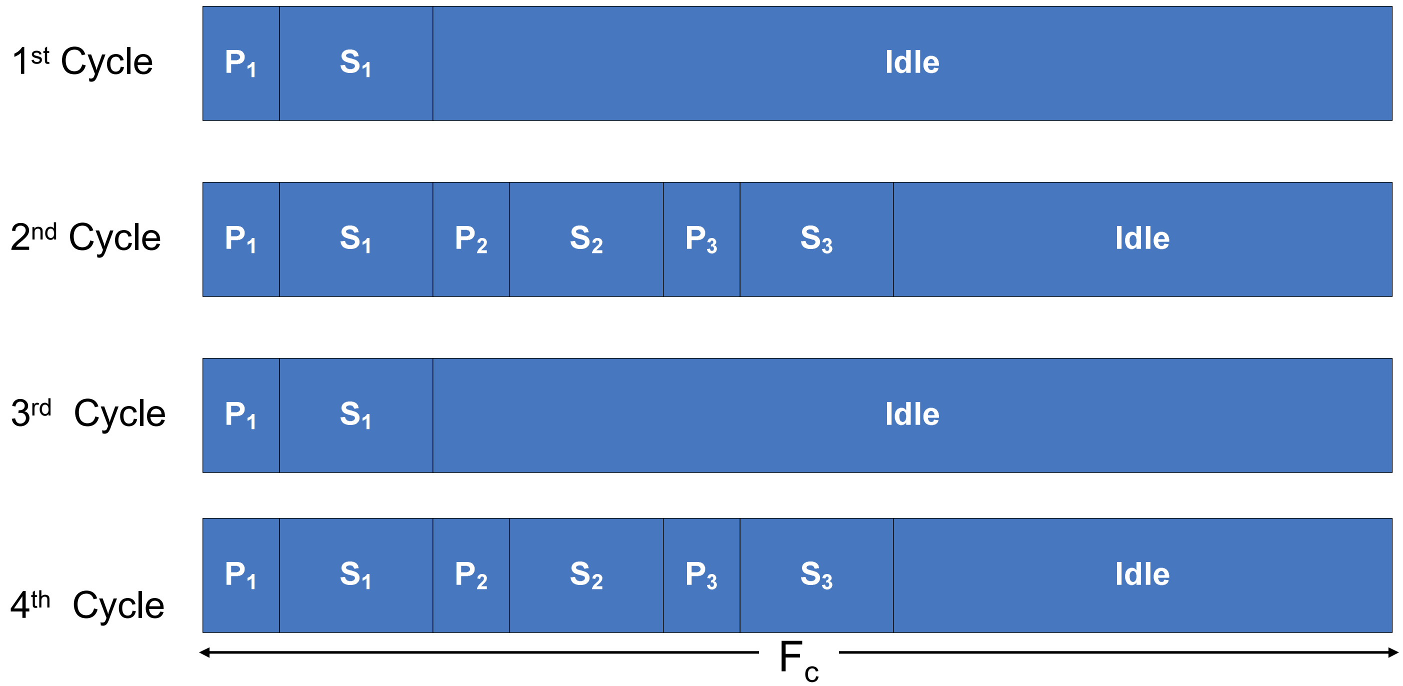
Below mechanisms are designed by following the MICS rules [2]

- Channel Access
- Emergency data transfer
- Co-existence

Channel Access Mechanism

1. Data Aggregation
   - Shorter packets suffer from greater overhead leads to energy inefficiency
   - Allow data aggregation at implant device to form optimal size packet over multiple cycles without violating the delay requirement
   - Aggregation of data is optional
2. Variable Polling Rate
   - Implant Arrival rate range: Few bytes/sec – 10 Kbits/sec
   - The implant devices will be polled with different polling rate according to their arrival rates.
   - This avoids power consumption of low data rate devices due to excessive polling
3. Static poll schedule for devices
4. Carrier Sensing is not preferred at implant device
   - Asymmetric Clear Channel Assessment
   - Power consuming

Frame Design for Implant Communication



- Fixed F_c allows static poll schedule
- Periodicity of Poll for a device is determined according to the arrival rate
- High rate devices are polled first to maximize idle time
- Idle time can be utilized for integration of implant communication with on body

Example

  - Device 1 is polled at F_c
  - Device 2 and Device 3 are polled at 2 F_c

Simulation Details for Implant

Application	Arrival rate/devices	Number of devices	Allocated slot time (S_i) per device (ms)
App 1	4 Kbps	3	1.53
App 2	2 Kbps	3	1.53
App 3	1 Kbps	4	1.53

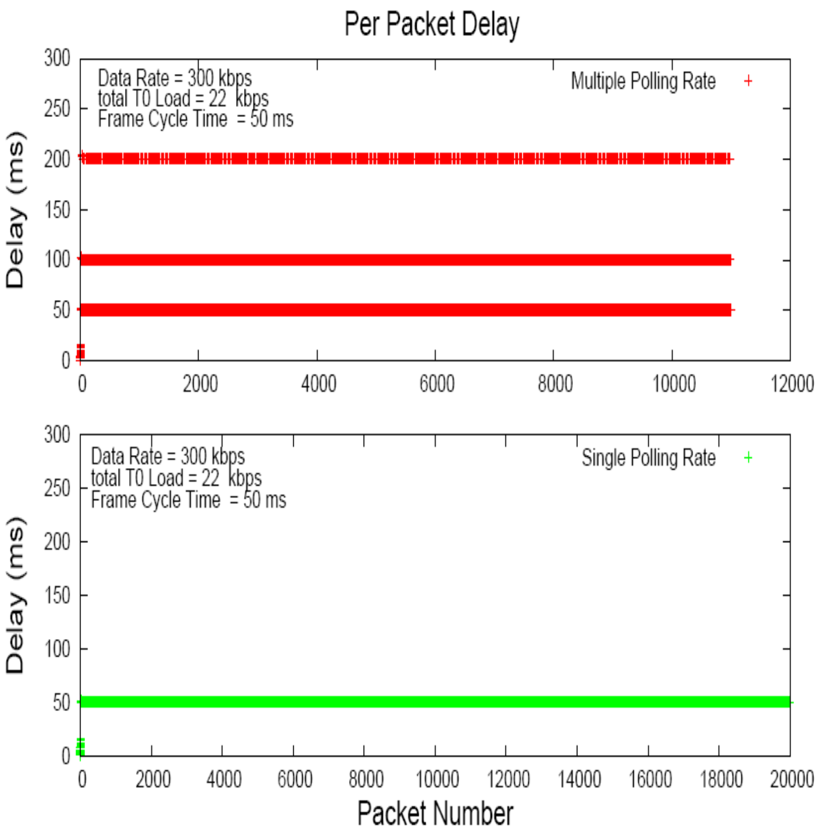
Data rate	300 Kbps
Total load	12 Kbps
Frame cycle	50 ms
IFS	196 µs
Poll size	15 bytes
ACK size	15 bytes

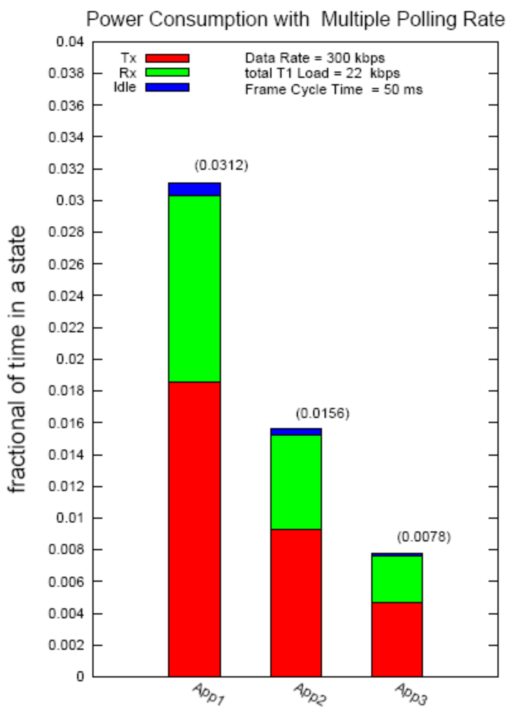
Delay: Queuing delay + Channel access delay + Transmission delay

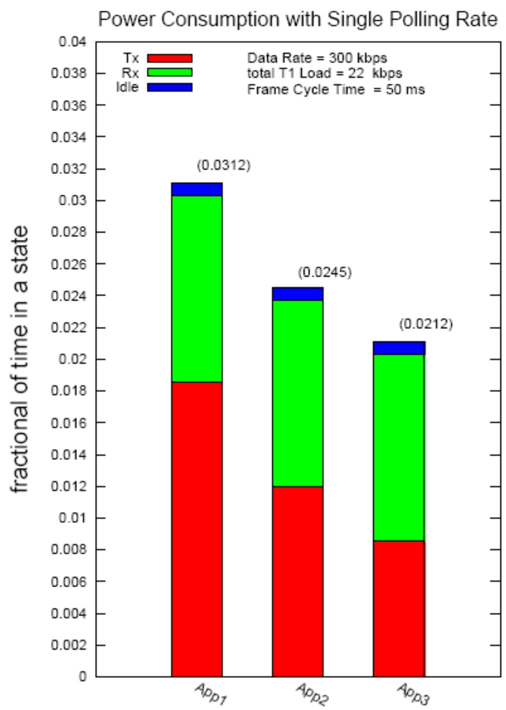
Power consumption: Total power consumption due to radio can be calculated from the time spent at different states

C++ based simulation framework is used to obtain all the simulation results

Simulation results for Implant – Delay and Power Consumption







Emergency data transfer

Objective:

Emergency data handling scheme should support fast and reliable transfer of emergency data

Challenges (when device is not active in a session):

- When emergency event occurs, device may not be aware
  - Whether Piconet is operational or non-operational ?
- Which channel to be used for emergency data transfer when Piconet is non-operational ?
- Channel can not be pre-reserved for network operations in MICS band

Mechanism:

- Piconet is non-operational
  - Coordinator duty cycles on a channel when Piconet is non-operational
  - Ordering of channels for duty cycling
- Piconet is operational – Forced collision

Emergency data transfer

Coordinator behavior – when Piconet is non-operational

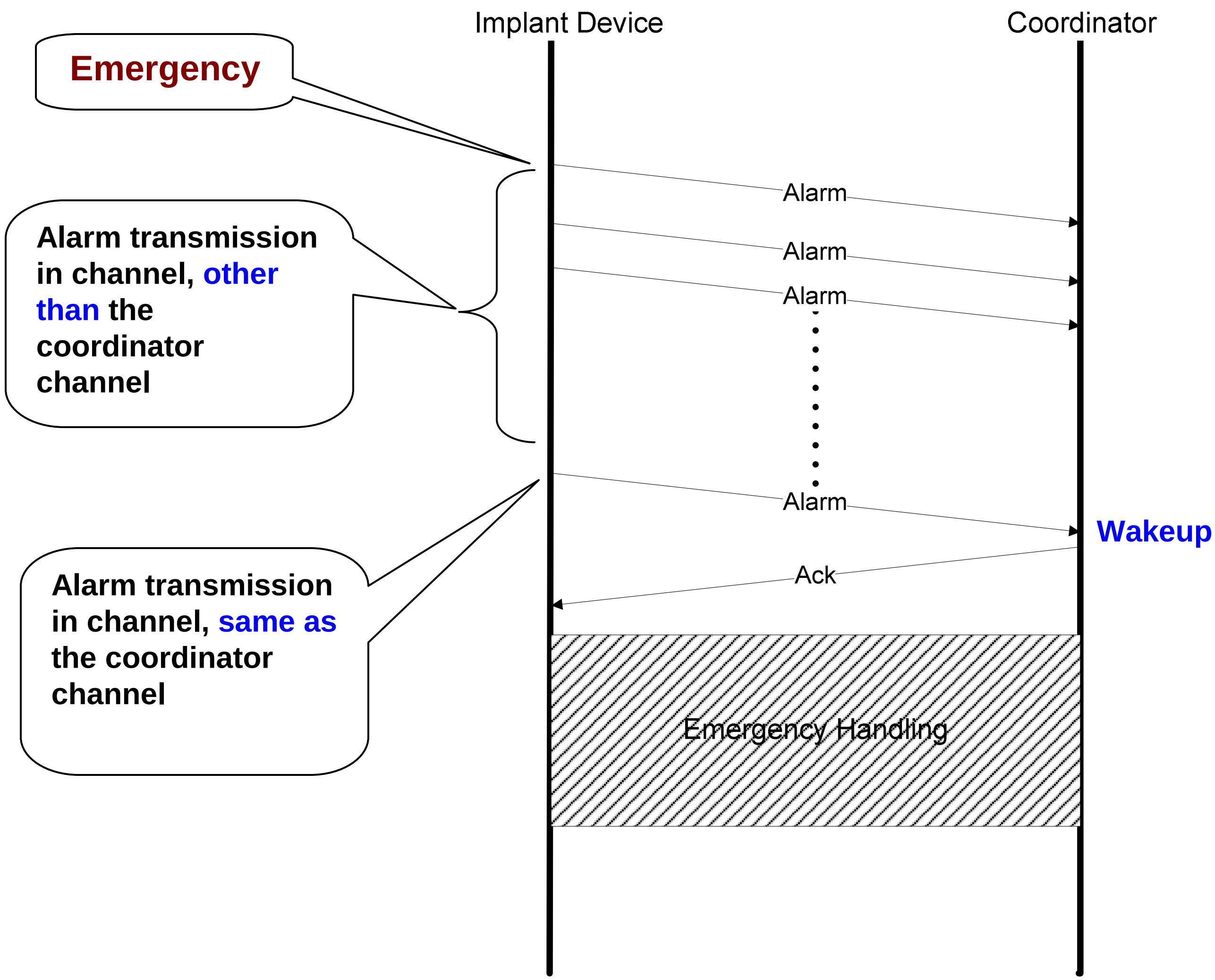
- Channel ordering is known to the coordinator and device
- Based on the channel order, Perform LBT to select a primary interference free channel for duty cycling

Events occur during duty cycling	Action taken by the coordinator
Detection of primary or secondary interference	Perform LBT to duty cycle on highest possible order interference free channel
Internal timer expires	Perform LBT to duty cycle on highest possible order interference free channel
Detection of emergency data	Send an ACK packet and handle emergency

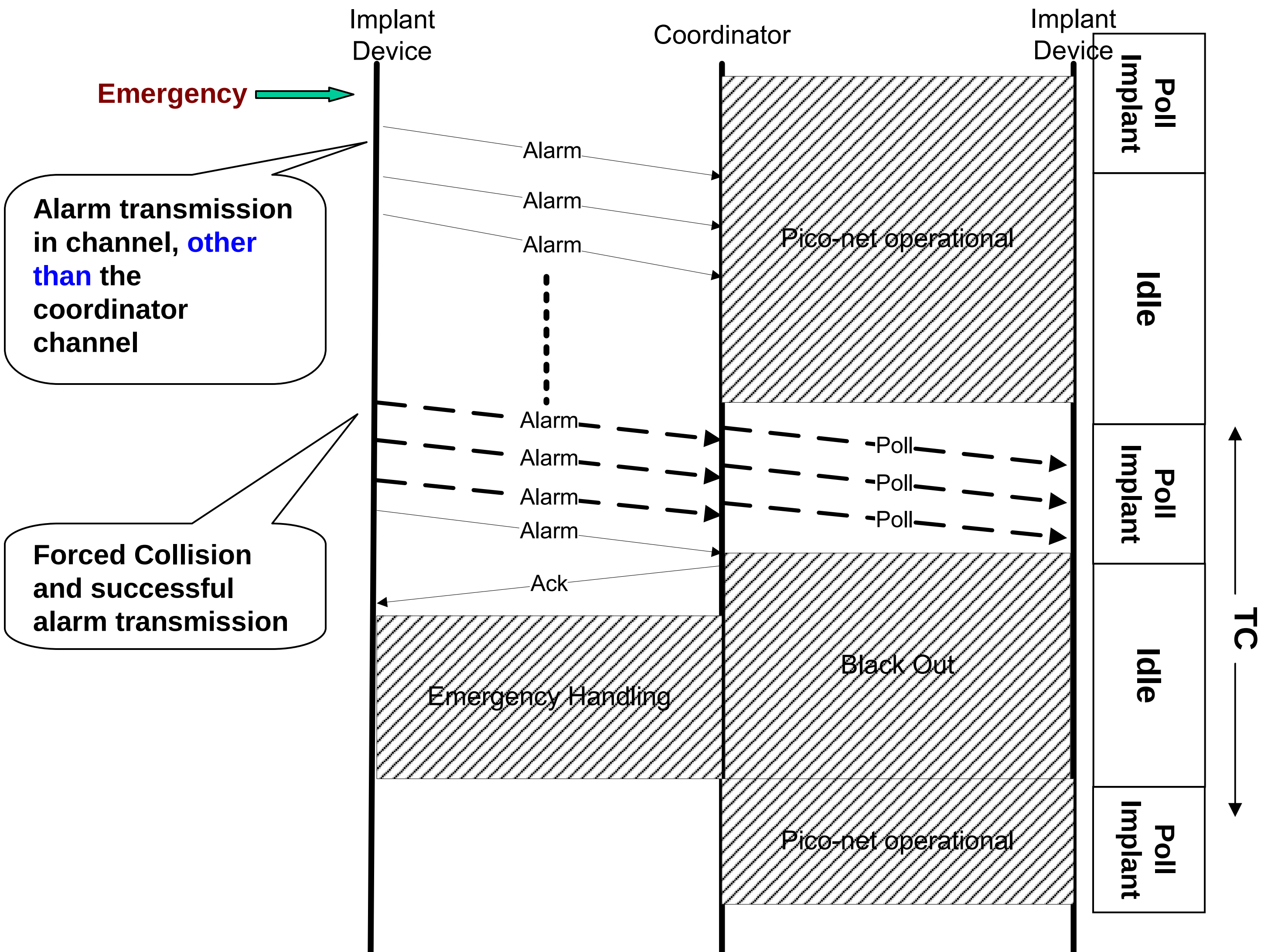
Device behavior – when emergency event occurs

- Send multiple alarm messages on the highest order channel and wait for an ACK
- ACK received, transfer emergency data
- Repeat step 1 according to the channel order till ACK is received

Emergency Handling: When Piconet is not operational

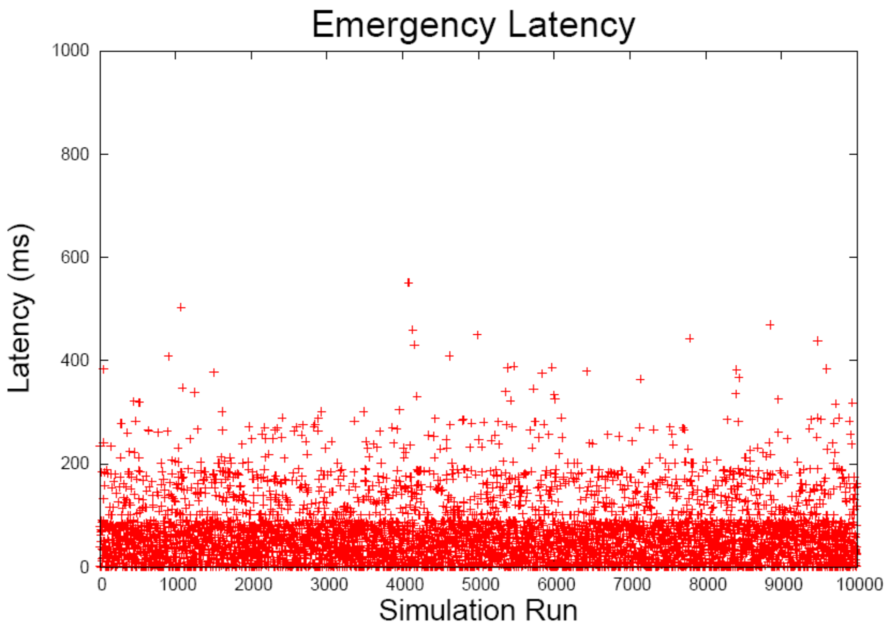


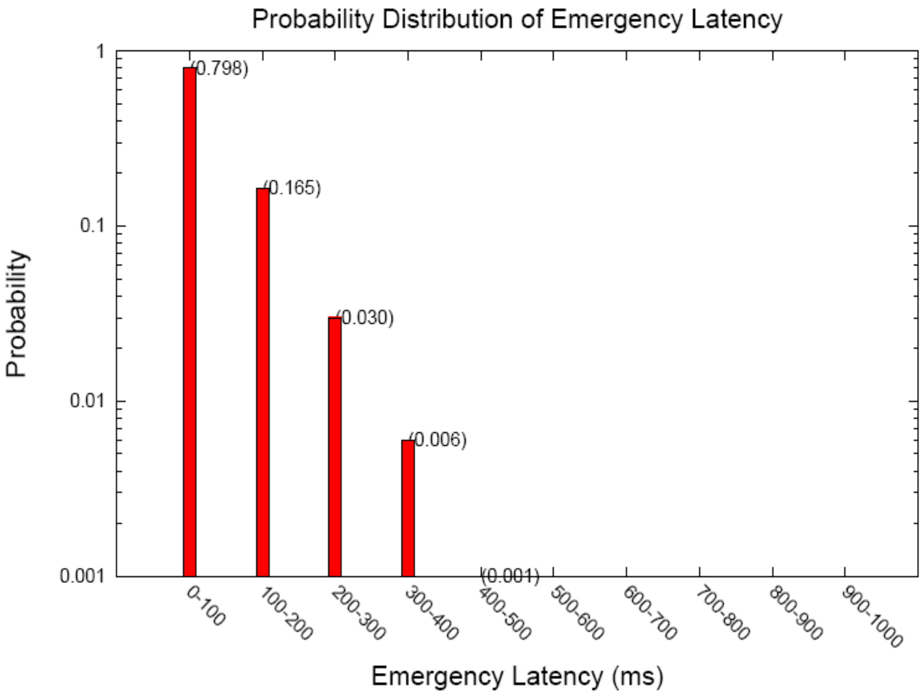
Emergency Handling: Coordinator is Operational



Successful alarm message transmission after forced collision

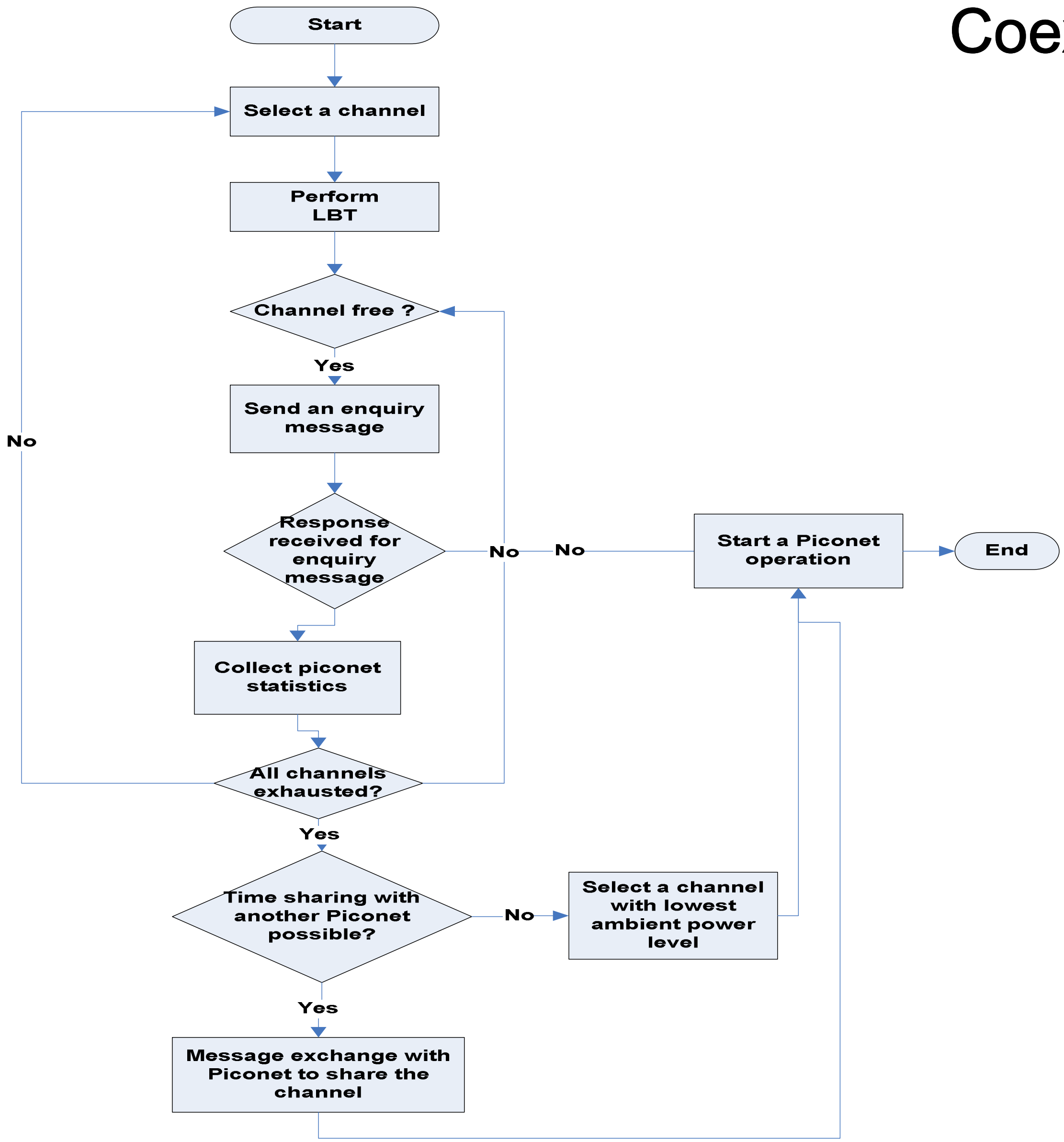
Simulation – Emergency





- An emergency is scheduled randomly in a simulation run
- Duration of a simulation run = 1000sec
- Number of simulation run = 10000
- 10 implant data sessions in a simulation run with each session duration of 10sec
- Duty cycle of coordinator = 10%
- One channel transmission time 100ms

Coexistence – Implant

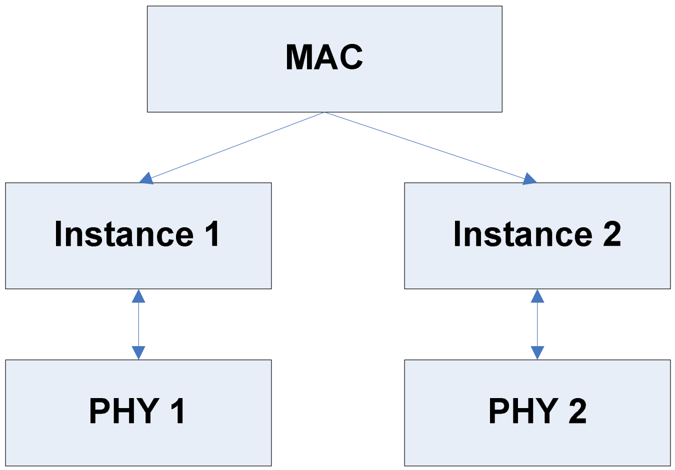


- Channel selection for network operation
  - Longer LBT may required to detect presence of secondary user (Energy inefficient)
  - Perform LBT for 10 ms and qualify access criteria
  - Send an enquiry message
  - Initiate network operation if no response
  - No free channel,
    - Time share with another Piconet, if possible
    - Else, select a channel with lowest ambient power level

Single MAC Design

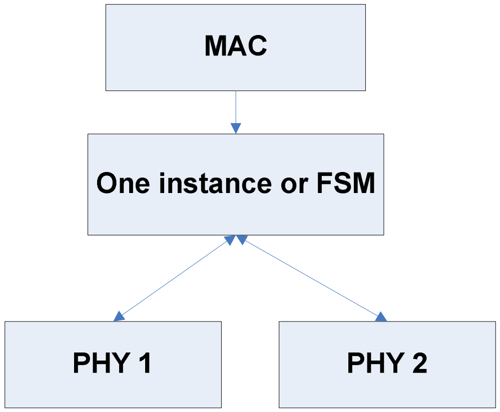
- Design Approach
- Single MAC Solution
- Piconet modes and device classifier
- Simulation results

Single MAC – Design Approach



Issues with two MAC Instances:

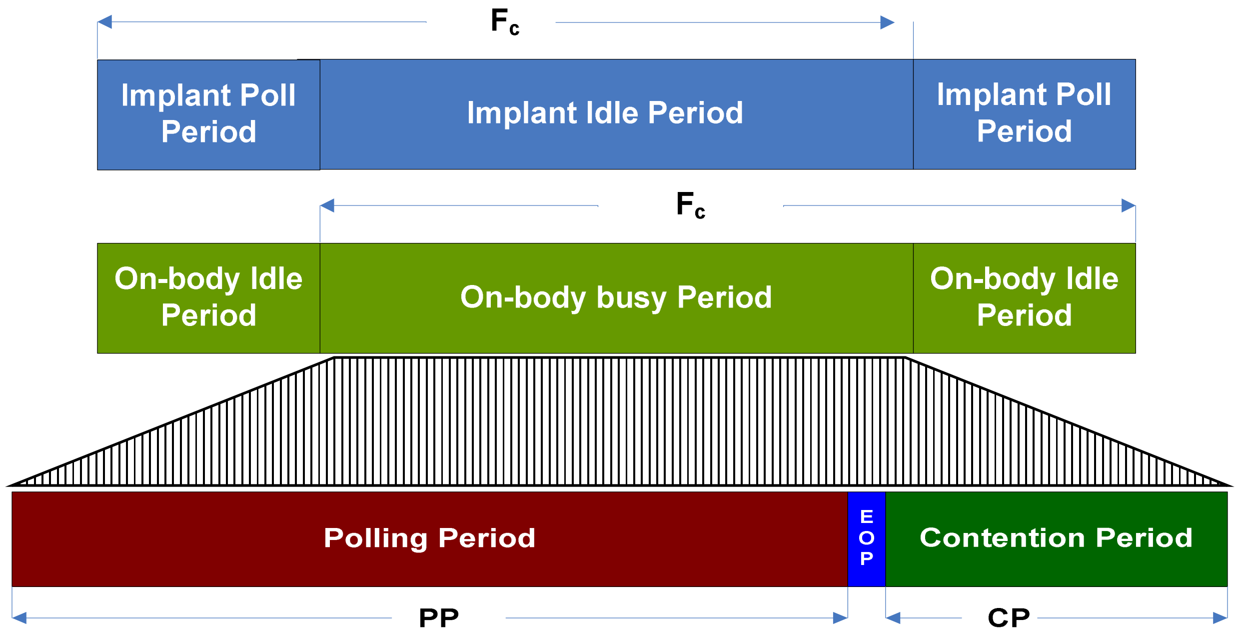
- Running two instances of a MAC or maintaing two MAC states….
    - Is it single MAC or two MACs?
- Firmware/hardware based co-design of MAC
    - It may be difficult to maintain two instances in hardware
- Complete firmware based design
    - Powerful processing unit is required
    - Complex to design



Approach:

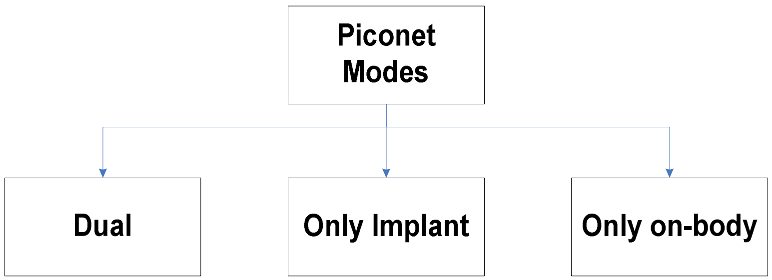
- One MAC state
- MAC time shares between PHY 1(Implant) and PHY 2(On-body)
- Implant communication is given priority over the on-body communication
- No degradation in performance of Implant

Single MAC Solution



- On-body data communication allowed in Implant idle period only
    - No degradation in performance of implant communication
- On-body busy period is designed based on the minimum Implant idle period
- On-body busy period consist of on-body poling period and on-body contention period

Piconet modes and Device Classifier



Device generate (X_1, X_2, X_3, X_4, X_5)

$X_i \in \{0, 1\}$, for i = 1 to 5

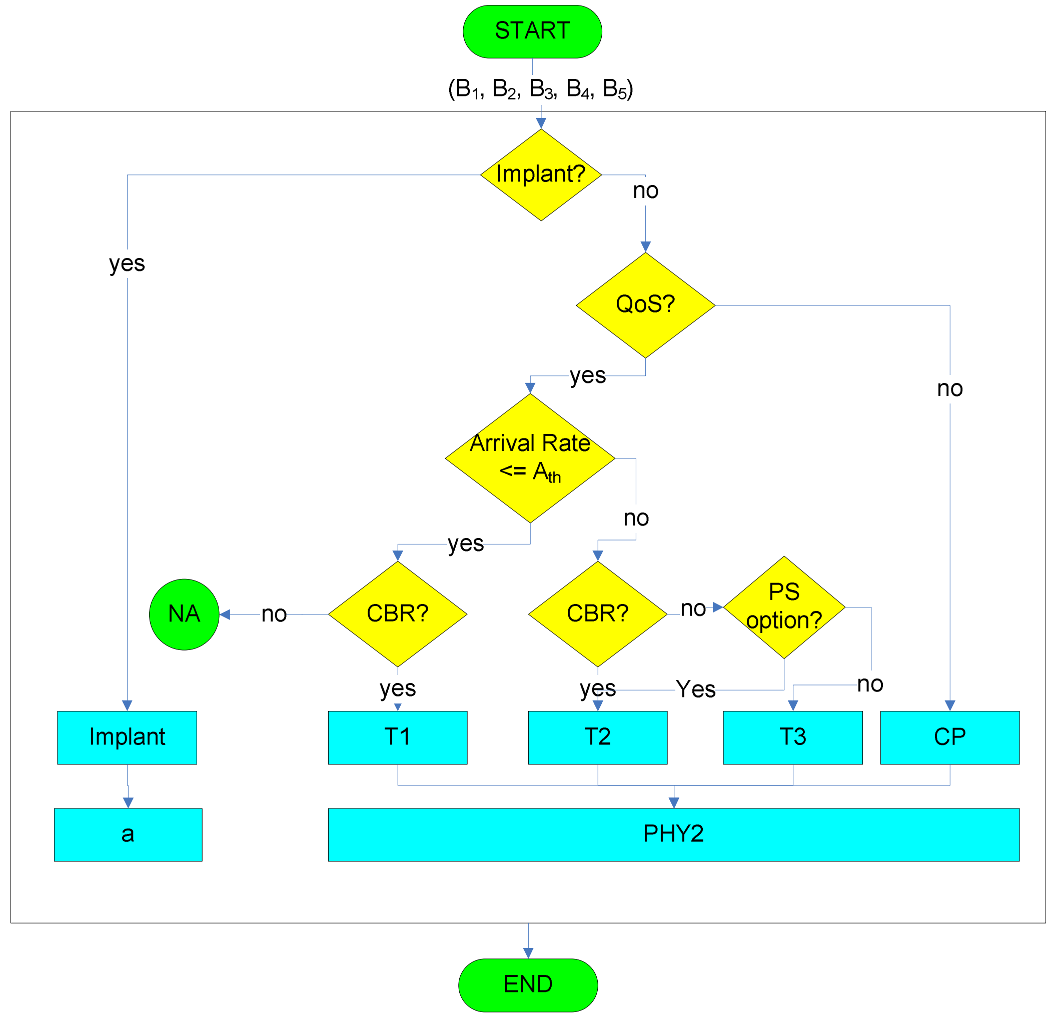
X_1: Scenario (Implant or on-body)

X_2: Best effort

X_3: Arrival rate

X_4: Traffic type

X_5: Power-saving option



Simulation Details for Dual Mode

Application	Arrival rate/devices	Number of devices	Allocated slot time (S_i) per device (ms)
ECG	4 Kbps	20	0.087
Vital Signal Monitoring	4 Kbps	20	0.087
EEG	8 Kbps	20	0.174
Interactive Gaming	4 Kbps	40	0.087
Fitness	4 Kbps	20	0.087
EMG	96 Kbps	96	1.433
Uncompressed Audio	64 Kbps	10	1.024

Simulation Run	40 sec
Data rate	10 Mbps
Frame cycle	115 ms
IFS	15 µs
Poll size	15 bytes
ACK size	15 bytes

T3 load: 3 Mpeg traffics

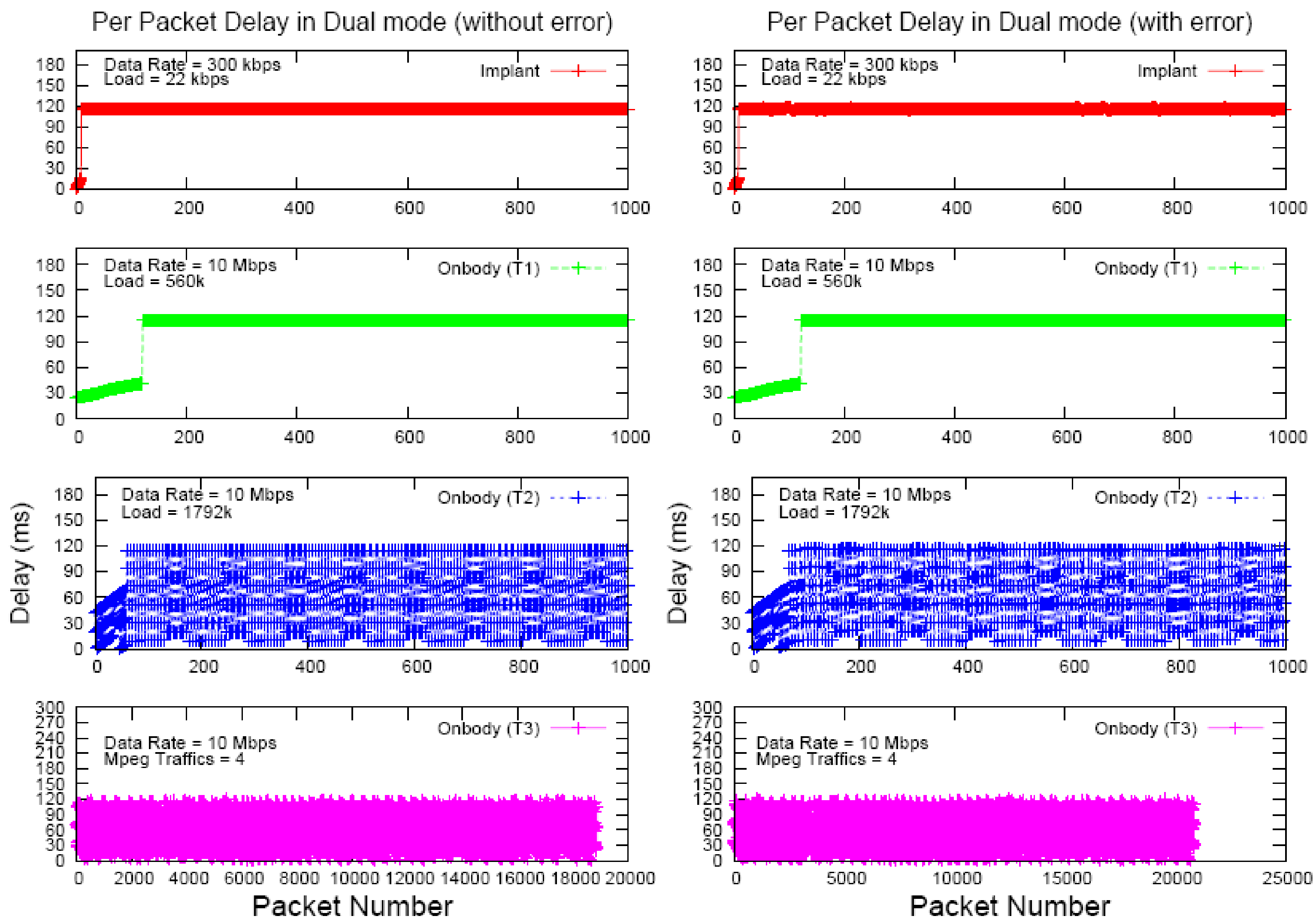
PHY 1

Application	Arrival rate/devices	Number of devices	Allocated slot time (S_i) per device (ms)
App 1	4 Kbps	3	1.53
App 2	2 Kbps	3	1.53
App 3	1 Kbps	4	1.53

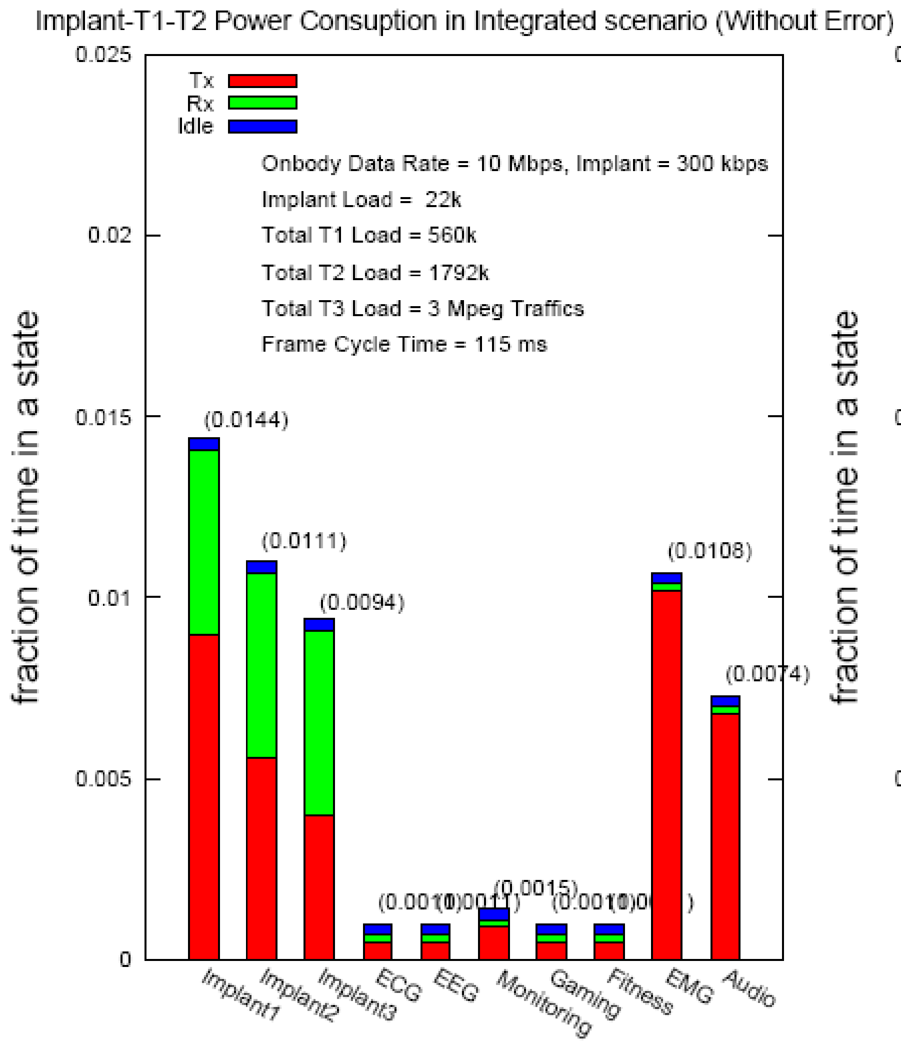
Data rate	300 Kbps
Total load	12 Kbps
Frame cycle	115 ms
IFS	196 µs
Poll size	15 bytes
ACK size	15 bytes

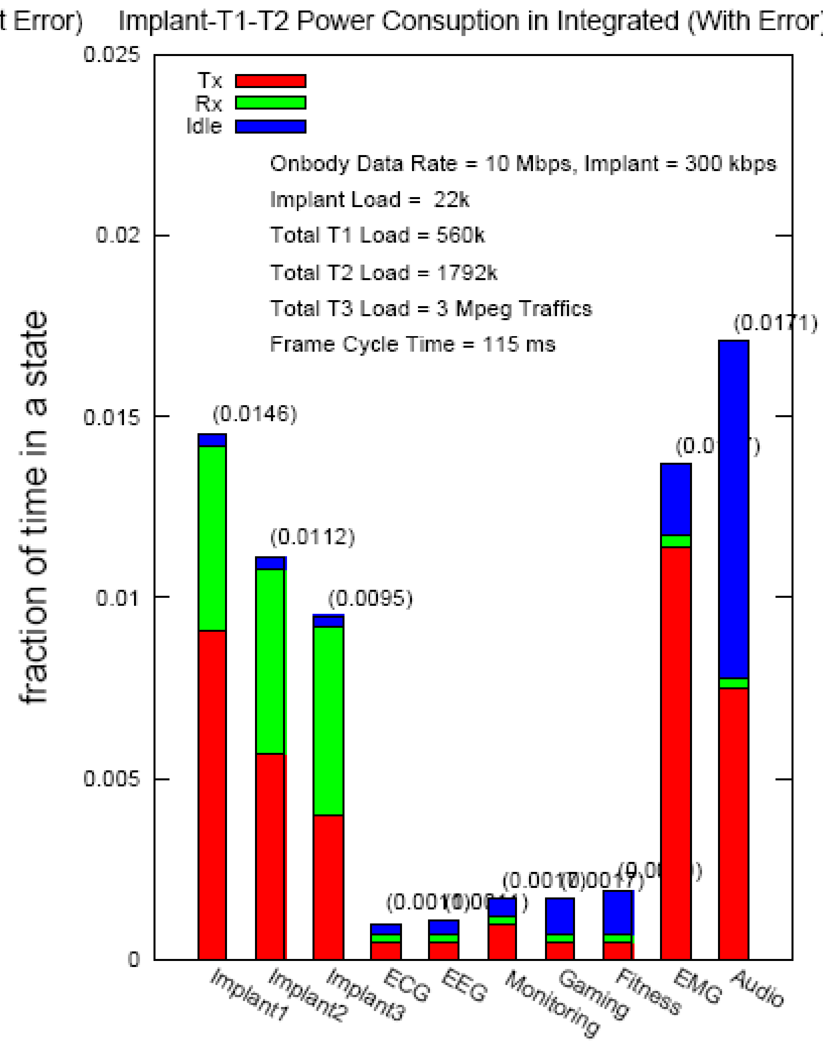
PHY 2

Simulation results for dual mode - Delay



Simulation results for dual mode – Power consumption





Comparison criteria and TRD coverage

Sl No.	Technical Requirements	Achieved (Yes/No)	Remarks
1	MAC transparency – Support of multiple PHYs	Yes	
2	Support of topology	Yes	Star topology, design can be extended to multi-hop star
3	Support of scalable data rate	Yes	Flexible channel access mechanism
4	Support of number of devices	Yes	Design can support load of 256 nodes with sufficient data rate is availability
5	Packet delay in Medical applications (< 125 ms)	Yes	
6	Packet delay in Non-medical applications (< 250 ms)	Yes	
7	Packet Delay Variation in Non-medical application (< 50 ms)	Yes	Subject to bandwidth availability
8	Low power consumption	Yes	

Comparison criteria and TRD coverage

Sl No.	Technical Requirements	Achieved (Yes/No)	Remarks
9	Availability of 99%	Yes	Subject to traffic load
10	Capability of providing fast (<1 sec) channel access in emergency situations (alarm messages)	Yes	
11	Time to associate a node to BAN	Yes	Association latency is reduced drastically in group based association scheme
12	Coexistence of 10 BANs in the proposed implant communication band	Yes	A Mechanism is proposed, simulation results yet to be obtained
13	Coexistence of 10 BANs in the proposed on-body communication band	Yes	A Mechanism is proposed, simulation results yet to be obtained
14	Support of security	Yes	Multi level security protocol is proposed

Conclusion

- The proposal minimizes power consumption at the expense of bandwidth utilization while meeting the delay and reliability requirements of the BAN applications
- No degradation in performance of implant communication in case of dual mode
- Single FSM for MAC leads to simple system implementation
- Most of the comparison criterions are covered

References

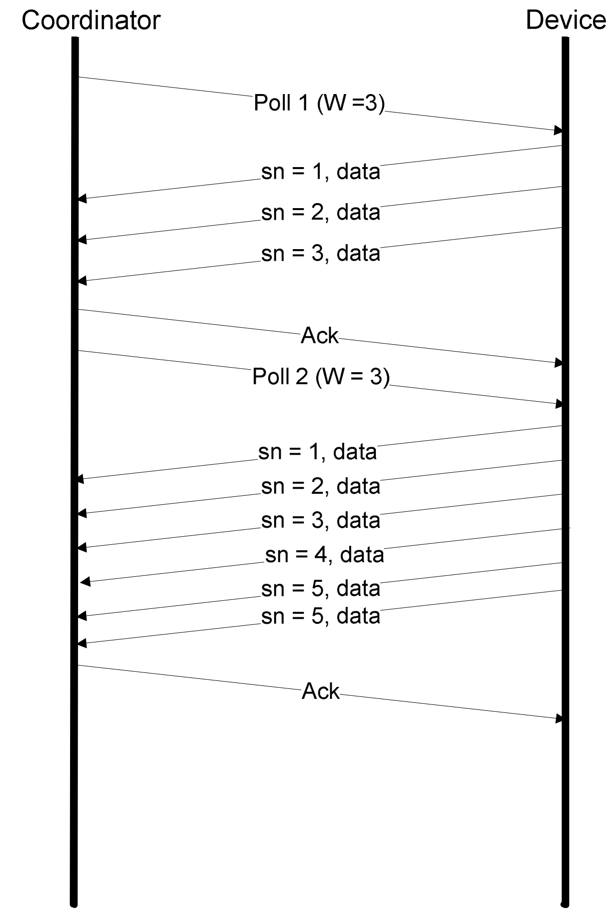
1. MPEG-4 and H.263 Video Traces for Network Performance Evaluation, http://www.tkn.tu-berlin.de/research/trace/trace.html.
2. “Medical Implant Communications (MICS)” Service rules part 95, http://wireless.fcc.gov/services/index.htm?job=service_home&id=medical_implant.

Additional slides

Polling mechanism for T3

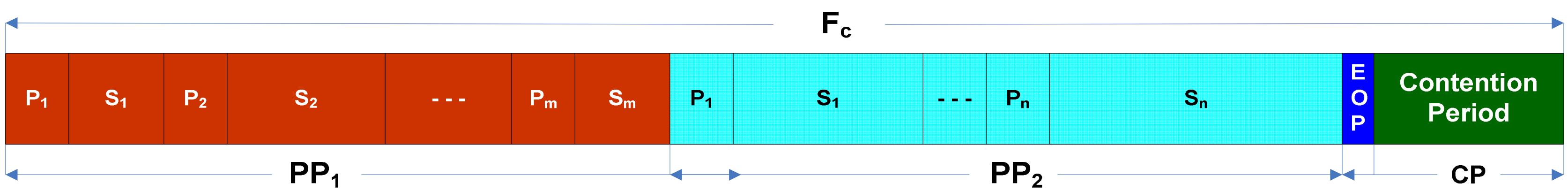
Error recovery mechanism:

- Error recovery mechanism same as in T2
- Packets are transmitted in phases
- Window size (W) is the maximum number of packets that can be transmitted in a phase
- All packets transmitted in a phase are successful
    - ACK is transmitted by the coordinator
- Any packet or poll is lost
    - Poll is transmitted to receive erroneous packets in the previous phase



Integrated Frame Structure

A. T1 and T2



Description:

- T_1 has highest priority
  - Bandwidth is reserved to support required applications in T_1, whenever T_1 coexist with other class of traffic
- Poll time is fixed for T_1 device even in co-existence scenario
- F_c is fixed, $F_c = PP_1 + PP_2 + CP$

Simulation Details for T1 and T2

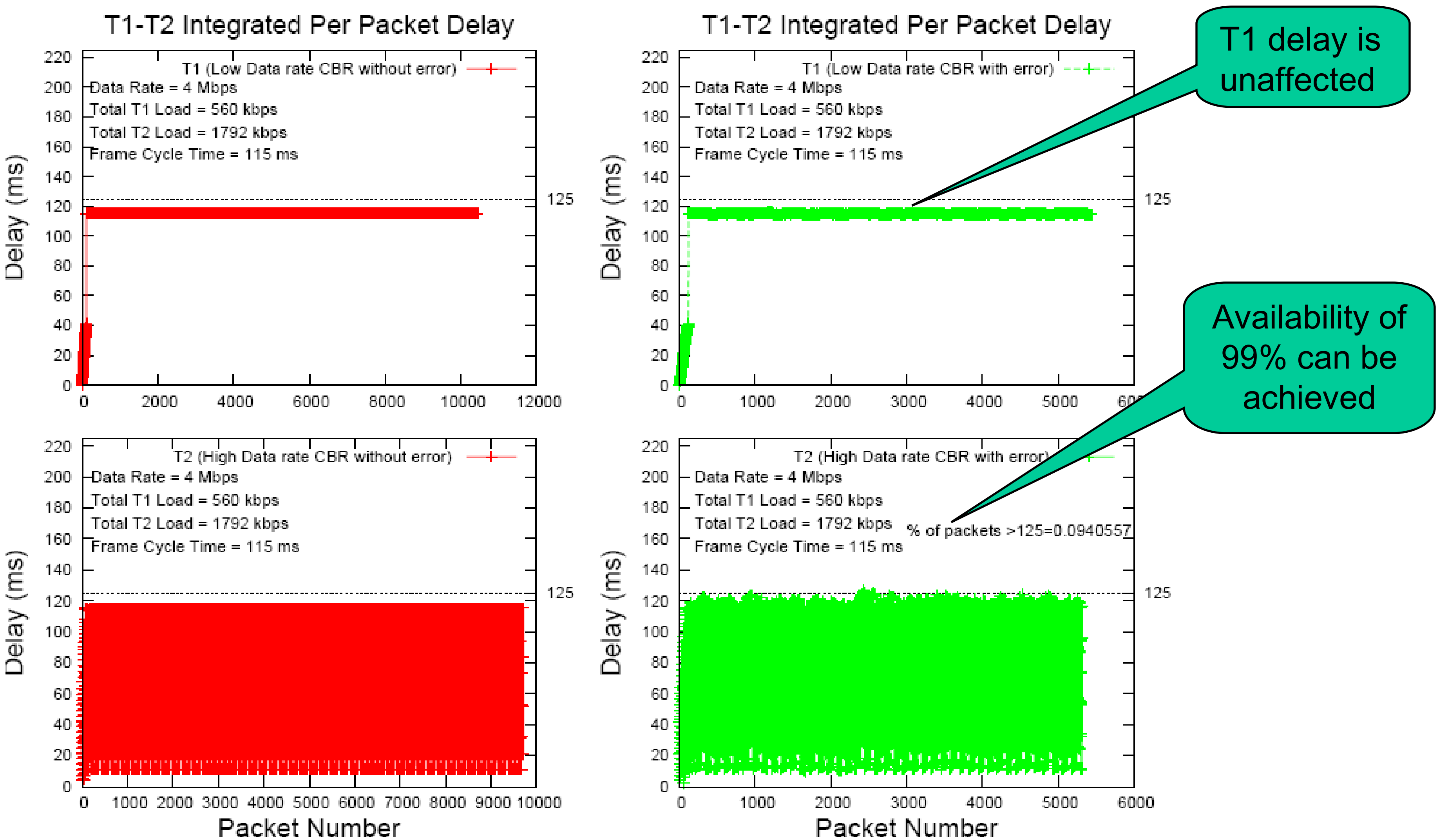
Application	Arrival rate/devices	Number of devices	Allocated slot time (S_i) per device (ms)
ECG	4 Kbps	20	0.218
Vital Signal Monitoring	4 Kbps	20	0.218
EEG	8 Kbps	20	0.436
Interactive Gaming	4 Kbps	40	0.218
Fitness	4 Kbps	20	0.218
EMG	96 Kbps	96	3.584
Uncompressed Audio	64 Kbps	10	2.56

Data rate	4 Mbps
Total load	2352 kbps
Frame cycle	115 ms
IFS	15 µs
Poll size	15 bytes
ACK size	15 bytes

Delay: Queuing delay + Channel access delay + Transmission delay

Power consumption: Total power consumption due to radio can be calculated from the time spent at different states

Simulation results of Integrated T1 and T2



Simulation results of Integrated T1 and T2