Buffering... energy for mobile devices: A "store and rendezvous" approach

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Motivation: Improve Energy Efficiency for Mobile Devices using DTN

- Mobile devices often undergo prolonged daily use
  - Battery capacity does not match the increased energy demand
- Wireless networking a major energy draining source
  - Up to 60% of the total energy consumption for network-intensive applications
- Goal: Reduce energy consumption of mobile devices
  - Wired-cum-wireless Internet setting with an 802.11 connection
- Observation: DTN can natively solve a wide-range of networking problems traditionally addressed with custom, isolated solutions
- Solution: Use DTN to shape Internet traffic and create long idle periods
  - Allow mobile devices to suspend the wireless interface during idle intervals
    - Setup rendezvous between Base Station and Mobile Receiver to flush data
  - Assess the effect on the user experience from applying this solution
  - Manage wireless channel utilization when multiple devices are active

Presentation Overview

- Related work on energy efficiency
- Background on DTN
- Energy-efficient networking with DTN
  - Energy-efficient DTN Overlay
  - Energy-saving potential (mathematical formulation)
  - Rendezvous mechanism
- Experimental methodology
  - In-house DTN simulation model in ns2
- Simulation Results
  - Simple DTN overlay, assessment of the effect on user experience
    - Experiment with different traffic types: FTP, CBR, HTTP
  - Multiple receivers with simultaneous FTP connections
    - Experiment with different scheduling strategies: isolated, combined, time-based
- Summarize conclusions and future work

Related Work

- Typical energy conservation solutions in wireless LANs
  - Rely on switching the WNIC to Sleep mode (Sleep power << Idle power)
  - Buffer data that arrive during sleep intervals
  - Are tailored to fit a certain traffic type
- 802.11 provides a built-in Power-Save Mode (PSM)
  - Mobile devices suspend their wireless interface and notify the Access Point (AP)
    - AP buffers incoming data destined to suspended nodes
  - AP includes pending data notification in a Traffic Indication Map (TIM)
    - Follows the periodic beacon frame
    - Mobile devices wake up periodically to listen to the TIM
  - Limited due to
    - Probabilistic nature of incoming data
    - Small buffer space at the Access Point
- Researchers have explored alternative methods
  - Based on the same core buffering principle

Related Work (2)

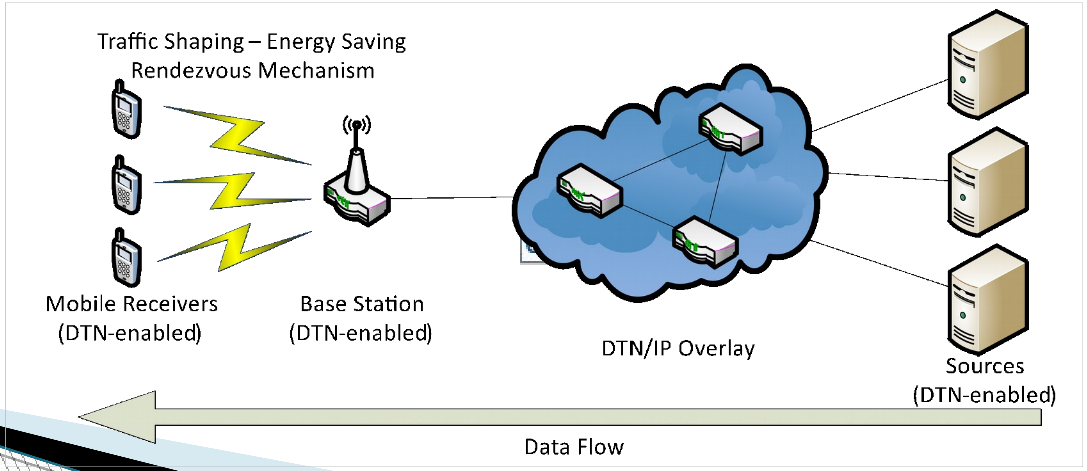
- Related work proposes solutions that extend or replace PSM
  - Data buffering at higher network layers, hiding traffic from PSM (Adams et al.)
  - Server-side proxy informing a client-side proxy of the next data arrival (Chandra et al.)
  - Scheduler service at the BS and a proxy at the mobile terminal (Zhu et al.)
  - Modified TCP version that utilizes round trip time estimates to selectively idle the wireless interface (Batsiolas et al.)
  - Most solutions target either streaming or file transfers
- Our solution: DTN overlay employing in-network data buffering
  - Use volume-based instead of time-based buffering
    - Completely bypass PSM
  - Incorporate signaling into the bundle protocol (in-band communication)
    - No need for additional agents
  - Targets both streaming and file transfers

DTN Background

- Copes with long propagation delays and intermittent connectivity
- Breaks the end-to-end connectivity constraint of Internet protocols
  - Provides asynchronous service
  - Allows for physically carrying data among isolated networks
- Can be deployed as an overlay on existing networks
  - Interconnects heterogeneous networks
  - Provides delay-disruption tolerant services among underlying network segments
- Provides permanent storage of protocol state and in-flight data
  - Ensures seamless operation across machine restarts
- Supports delivery reliability through the custody mechanism
  - A coarse-grained retransmission capability

Energy-Efficient DTN Overlay

- DTN overlay deployed in a typical Internet setting with a last-hop 802.11 link
  - Exploit excess capacity of the wireless link vs. the Internet connection
    - Shape incoming traffic creating long idle intervals
    - Allow mobile device switch the network interface to sleep mode
  - Minimum deployment: Source, BS, Mobile device
  - Presence of additional nodes exploits in-network storage pushing data closer to the BS
  - Hop-by-hop communication supports
    - The two main Internet transports TCP (FTP, HTTP) and UDP (media streaming)
    - Custody transfer
  - Bundles are routed in a cut-through fashion respecting space availability
- Extended DTN with a Rendezvous mechanism (between BS and device)



Energy-Saving Potential

- Simple mathematical formulation of ideal energy consumption
  - One-way traffic and constant incoming and outgoing data rates at the BS
  - All idle intervals are exploited as sleep intervals
  - Active States: Transmission (1.4 W), Reception (0.95 W), Idle (0.81 W), Transition (0.81 W)
  - Sleep State: Sleep (0.06 W)
- Observations
  - Tradeoff between energy conservation and data delivery latency
  - Large transition times and small outgoing/incoming data rate ratios require large buffering amount
  - For multiple active receivers, each flow OutRate becomes smaller, and the energy-saving potential is reduced
    - Energy-efficiency improves if flows do not overlap
- Example state transitions for
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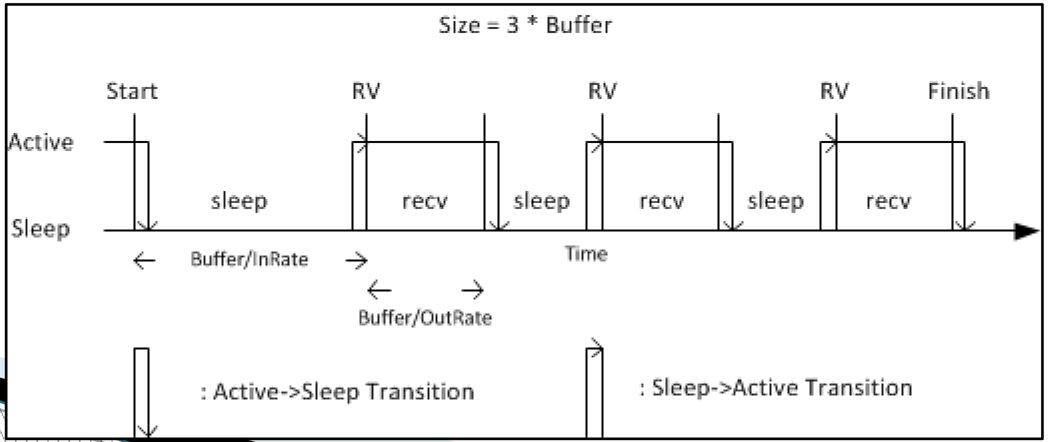
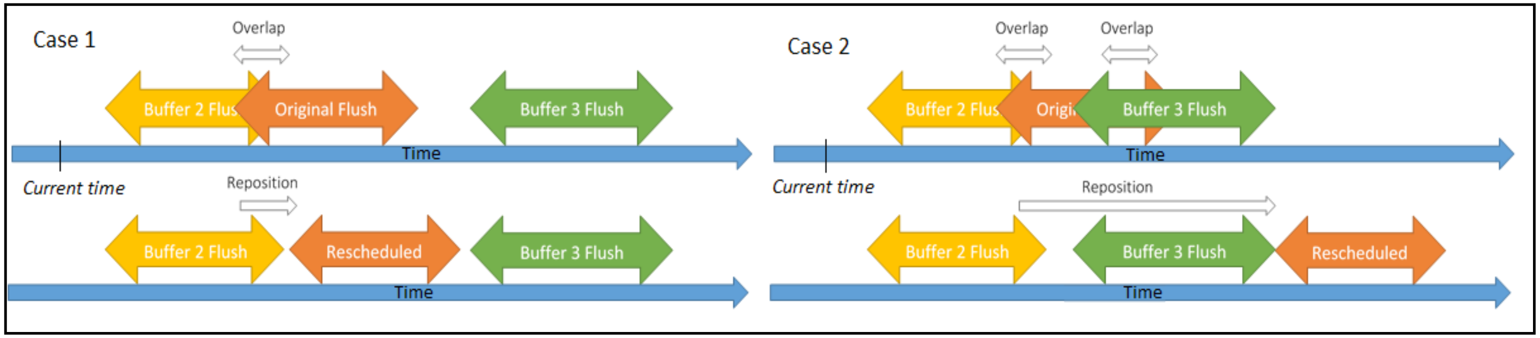


The Rendezvous Mechanism

- Data are withheld at the BS and flushed at rendezvous times
  - The desired buffering amount is specified via the Target Buffer Occupancy (TBO)
  - Partially received bundles are fragmented
    - Creating a fully received fragment (forwarded) and an empty fragment (remains at the BS)
- Each rendezvous is calculated based on a smoothed ratio (SBP) of the received bytes (RB) during the previous reception interval (RI) and the TBO
  - ,
  - Calculated rendezvous time is included at the end of burst in the bundle header
- Mobile device checks for sufficient time and suspends the wireless interface until the next rendezvous (considering time for transition)
- In case of multiple receivers the energy efficiency can be improved by limiting transmission overlaps
  - Limiting transmission overlaps results to shorter flushes
  - Receiver remains active for shorter periods of time

Limiting Transmission Overlaps

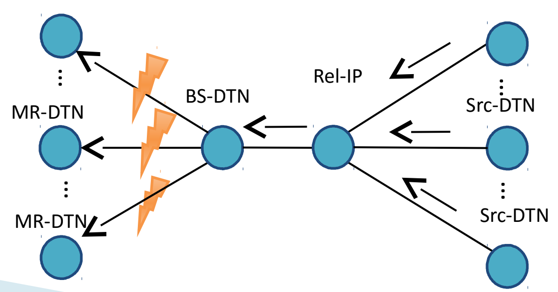
- Experimented with alternative rendezvous mechanisms: isolated, time-based, combined
- Isolated (original): Rendezvous' are set with each receiver individually (i.e. no transmission overlap limitation)
- Combined (improvement): BS takes into account scheduled rendezvous' of other receivers
  - NextRV is calculated according to the original mechanism
  - The BS detects possible overlaps with already scheduled transmissions
    - Estimating the average flushing duration based on the wireless link nominal bandwidth and the TBO
  - Repositions the rendezvous earlier or later in time so that overlaps are avoided
    - Minimize time shifting of the rendezvous



- Time-based (benchmark): BS schedules rendezvous in a purely time-based fashion
  - Buffer flushes alternate in equal time intervals and overlaps are avoided (flushes are scheduled adequately far apart)
  - Intervals are predetermined based on data gathered from the combined algorithm simulations

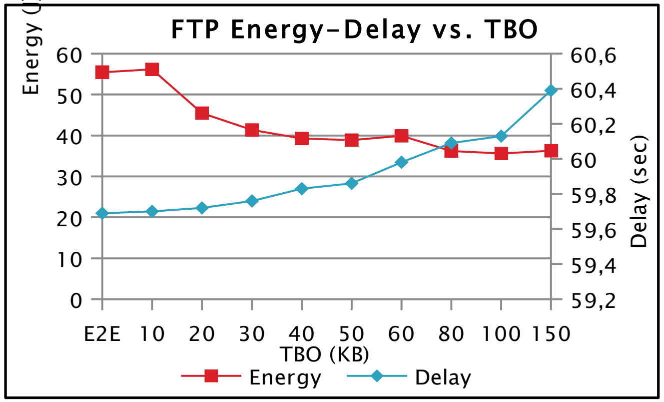
Experimental Methodology

- Simulations with our in-house DTN simulation model implemented in ns2
  - DTN agent supports both TCP and UDP
    - Store-and-forward module between the application and the transport layers
- Two main simulation directions
  - Single wireless receiver: Evaluate solution performance and user experience effect for
    - File transfers (FTP): Sending a file of 10 MB
    - Media streaming (CBR): Sending 500 B every 5 ms (800 Kbps) for 1 minute
    - Web browsing (HTTP): Sending files of 20 KB for 2 minutes and 40 seconds (each file is sent as soon as the previous file arrives)
  - Multiple wireless receivers, different transmission scheduling strategies for file transfers of 10 MB: isolated, combined and time-based
- BS-MRs connected on an 802.11 WLAN, with a data rate of 11 Mbps
  - Energy expenditure for the WNIC of mobile devices is tracked by the ns2 energy model
- Nodes with the DTN suffix host a DTN agent, Rel-IP node relays IP traffic
  - IP route: Src-DTN→Rel-IP→BS-DTN→MR-DTN
  - Overlay transfers: Src-DTN→BS-DTN→MR-DTN
  - End-to-end transfers: Src-DTN→MR-DTN



Results: Single Receiver FTP

- E2E: Energy 55.5 J, delay 59.7 sec
- 80 KB TBO: Energy 36.2 J (34% improvement), delay 60.1 (0.7% increase)
  - Insignificant additional delay (maximum of 0,4 sec)



- 10 KB TBO: Practically no sleep (not enough time for transition)
- TBO >= 20 KB: Overall idle > 25 sec (sleep + transition)
- 80 KB TBO: Sleep time of 26 sec

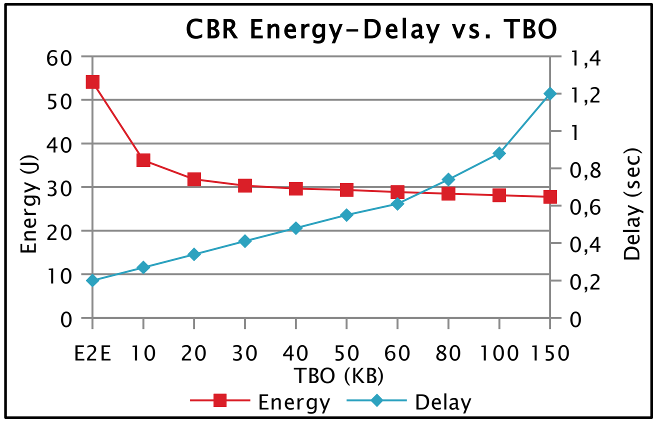
State Statistics vs. TBO

TBO	Sleep Count	Sleep Time	Trans Time
E2E	0	0	0
10	232	2.39	4.62
20	521	14.93	10.36
30	348	19.93	6.9
40	262	22.47	5.18
50	212	23.04	4.16
60	176	22.74	3.48
80	134	26.42	2.62

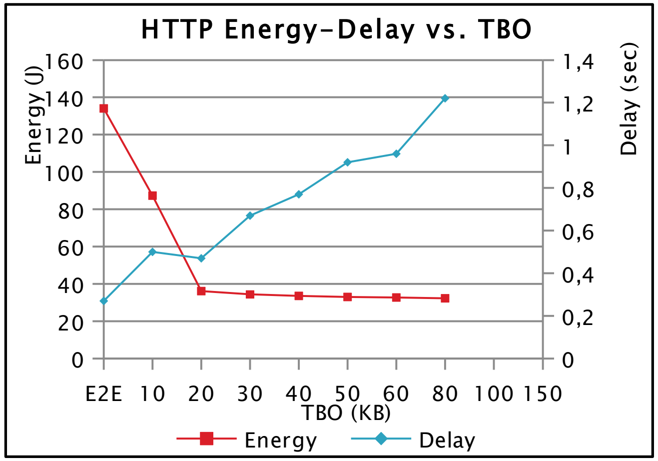
- User experience: File transfers marginally affected by buffering in the DTN overlay
  - TBO value much smaller than the ADU (i.e. the transferred file) leading to negligible additional delay

Results: Single Receiver CBR - HTTP

- E2E: Energy 54.1 J, delay 0.2 sec
- 10 KB TBO: Energy 36.1 J (-33%), delay 0.27 sec (+26%)
- 30 KB TBO: Energy 30.3 J (-44%), delay 0.41 sec (+100%)
- 80 KB TBO: Energy 27.7 J (-47%), delay 1.2 sec (+ 370%)
- User experience: Significant delay increase at the datagram level
  - Could be compensated by a small increase of the client buffering
  - 30 KB TBO: Additional delay (200 ms) hardly noticeable by the end-user

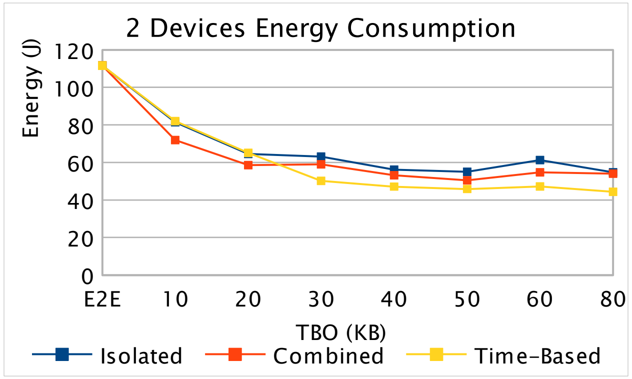


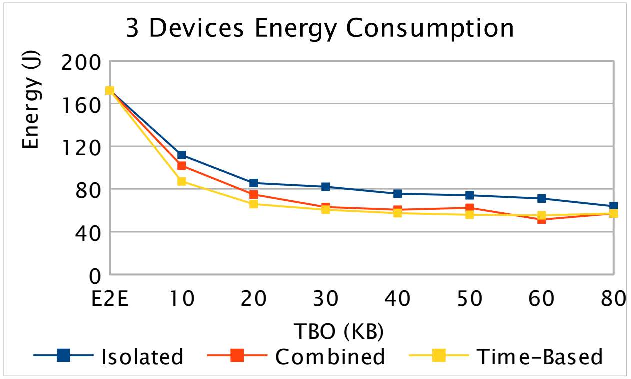
- E2E: Energy 134.1 J, delay 0.27 sec
- 20 KB TBO: Energy 36.2 J (-73%), delay 0.47 sec (+74%)
- Large energy savings (long idle periods between successive ADUs)
- Key value of 20 KB TBO coincides with the file size of 20 KB
- Web browsing user experience is sensitive to the application responsiveness
  - Introduced delay may deteriorate user experience and should be employed with prudence
  - Possibly require user's consent when battery level is running low

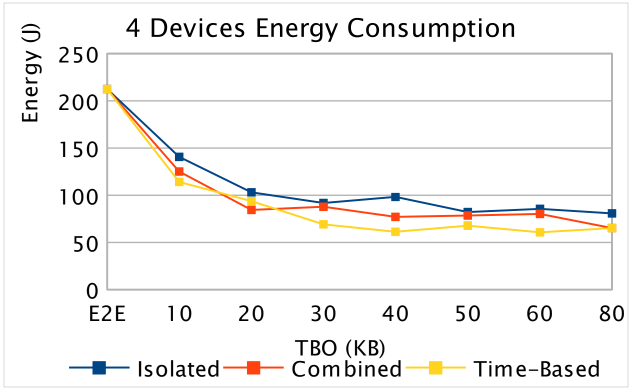


Results: Multiple Receivers File Transfers

- 2 Devices
  - Combined vs. isolated (all TBOs): Improvement of 10-15%
  - Time-based vs. isolated (TBOs >= 30 KB): Improvement of >15%
  - Few devices smaller differences
- 3 Devices
  - Combined and time-based mechanisms vs. isolated (TBOs between 30 and 60 KB): Improvement up to 25%
  - Similar performance of the combined and time-based mechanisms
    - Flush fitting mechanism effectively limits contention
- 4 Devices
  - Combined vs. isolated (all TBOs): Improvement of 5-20%
  - Time-based vs. isolated (TBOs between 30 and 60 KB): Average improvement of 30%
- Minimizing overlap of the buffer flushes significantly improves the energy efficiency of the mobile receivers
  - The combined mechanism improves energy efficiency over the isolated mechanism
    - However it exhibits relatively inconsistent performance (it is possibly unable to eliminate overlaps under all circumstances)
    - Further refinement of the mechanism is necessary

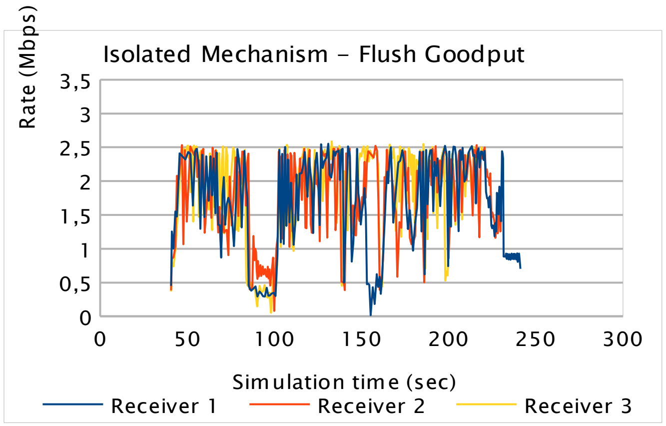


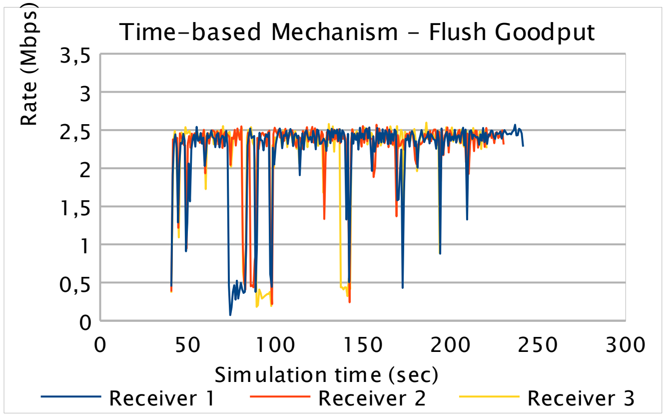




Results: 3 Devices Flush Goodput

- Top: Isolated 40 KB TBO, energy 75 J
- Bottom: Time-based 40 KB TBO, energy 57 J
- The isolated mechanism goodput fluctuates within a wide range
  - Multiple buffer flushes may be simultaneously active
  - Lower goodput results in longer flush duration => the WNIC must stay active for longer periods of time at each rendezvous
- The time-based goodput is contained within a narrow band below the 2.5 Mbps value
  - Rapid buffer flushes achieve better energy efficiency of the receiver
  - The time spent in the sleep state is maximized over the time spent in the idle state





Conclusions

- Simulation experiments in-line with mathematical formulation and older results
- File transfer energy efficiency improvement > 30%, performance only marginally affected by the DTN overlay
  - ADU (file) size >> buffering amount (TBO)
  - The proposed energy-efficient solution does not deteriorate end-user experience and can be unconditionally applied
- Streaming energy efficiency improvement > 40%, performance can be affected for large TBOs
  - ADU (datagram) size < buffering amount (TBO)
  - Introduced delays can be compensated for by a slight increase in the client buffering amount
    - Maintaining high level of user experience
- Web browsing energy efficiency improvement > 70%, performance affected
  - ADU (average file) size ≈ buffering amount (TBO)
  - User experience during web browsing highly dependent on responsiveness
    - Soliciting the user’s consent may be necessary

Conclusions (2)

- When multiple devices are present
  - A smart scheduling mechanism that limits overlaps of the buffer flushes further improves energy efficiency
  - Our combined mechanism improves on the isolated approach, but it is not as consistent as the time-based mechanism
    - Further development of the mechanism is necessary
- Future plans
  - Refine the combined mechanism increasing its flexibility and adaptiveness to changing network conditions
  - We have strong evidence that energy efficiency could be significantly increased if the overlap calculations dynamically adjust based on
    - The load of the WLAN
    - The expected data amount available at rendezvous time

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