

Lifetime-Aware Hierarchical Wireless Sensor Network Architecture with Mobile Overlays

Maryam Soltan, Morteza Maleki, and Massoud Pedram
University of Southern California
{soltan,morteza,pedram}@usc.edu

ABSTRACT— Recent technological advances have led to the emergence of small battery-powered sensors with considerable, albeit limited, processing and communication capabilities. Wireless sensor networks have therefore gained considerable attention in applications where spatially distributed events are to be monitored with minimal delay. We present and analyze a hierarchical wireless sensor network with mobile overlays, along with a mobility-aware multi-hop routing scheme, in order to optimize the network lifetime, delay, and local storage size. Fixed event aggregation relays and mobile relays are used to collect events from the sensors and send them to a central base station. We analyze the effects of various system parameters on the network performance, and formulate a convex optimization problem for maximizing the network lifetime subject to constraints on local storage, delay, and maintenance cost. Network behavior is studied and analytical results are validated through extensive simulations.

I. INTRODUCTION AND PRIOR WORK

A key technical challenge in most Wireless Sensor Networks (*WSN*) is how to effectively deploy and coordinate the sensors and how to manage data collection in order to achieve a minimum end-to-end delay, a maximum Monitoring Lifetime (*MoL*), and a desired Quality of Monitoring (*QoM*). *MoL* is duration of time that monitoring service is provided while *QoM* captures achievable performance and accuracy of data. Both of these parameters depend on sensor initial energy, deployment density, placement, sampling rate, network connectivity, and communication cost.

Several *WSN* architectures have been proposed for various applications. A simple one is a *flat* architecture where sensors also act as routers and transfer data through multi-hop routing. To better utilize limited communication and computation power of the sensors, a two-tier network may be employed [1], where more powerful fixed or mobile relays are used to collect and route the sensor data. With fixed relays, however, non-uniform sensor-to-relay distances require that the sensors closer to relays also transmit information originated from other sensors. This leads to a heterogeneous network with a non-uniform depletion rate of energy sources and hence shorter lifetime. Since regular battery replacement in a large network is not a feasible solution, we consider mobile relays. Mobility assisted data collection in different applications of *WSN* has recently been discussed in the literature [2-7]. Most of the prior work, however, has been focused on single-hop communication to the mobile node.

Our main contributions in this paper are to analyze the effect of mobility in a multi-tiered wireless sensor network under multi-hop routing and to present a mobility-aware routing scheme. Specifically, we consider a *WSN* architecture, which consists of three hierarchical levels of sensors, Event Aggregation Relays (*EAR*), and Mobile Aerial Infrastructure overLay (*MAIL*) nodes. The sensors are deployed in spatially distributed groups where each group is assigned a fixed *EAR* node. *EAR* nodes are low

power event processing and data relay devices, which collect data through single-hop communication with the sensors, process local events and transmit data packets, through multi-hop wireless communication, to the *MAIL* nodes. Finally, mobile *MAIL* nodes forward data to the base station. Using aerial vehicles is especially helpful when terrain contains many blockages, e.g., mountainous regions, and ground-to-ground communication over large distances is not efficient due to large signal attenuation.

We exploit the mobility to increase *MoL* by reducing and balancing power consumption of sensor and *EAR* nodes. More precisely, we analyze the effects of velocity and communication power of *MAILs* on network lifetime, delay, and local storage buffers. Furthermore we propose a multi-hop routing scheme in the *EAR* layer, which considers mobility and queuing delays, in order to improve network performance, size of buffers, and network maintenance.

First we discuss our network structure and parameters. Then in sections III and IV we present our routing scheme as well as our analytical results on the effects of various system parameters on network performance. In section V we show how the constrained lifetime maximization can be formulated as a convex optimization problem. Finally, we present our system behavioral studies as well as our simulation platform and simulation results.

II. NETWORK STRUCTURE AND PARAMETERS

Figure 1 depicts our hierarchical *WSN* architecture comprising of sensor, *EAR*, and *MAIL* nodes. Sensors are deployed on the boundaries of a closed region, such that a minimum *QoM* is achieved. Possible applications of this type of sensor deployment are oil and gas refinery protection, borders or battlefield surveillance, oil pipeline safeguarding, etc. Sensors are grouped based on their location and their data reporting rate such that the groups have a balanced data generation rate. Each sensor in a group directly communicates to its associated *EAR*. *EAR* nodes are fixed low power data relay nodes that collect data and route it to a nearby *MAIL* node, and hence reduce communication burden on sensors and add more power control flexibility. Finally each *MAIL* directly forwards the data to the central base station.

Sensors are very low power devices with short-range transmitters, while *EAR* nodes are battery-powered devices with capability of routing and communicating with aerial vehicles. *MAIL* trajectory is determined based on the location and the data traffic of *EAR* nodes. In this paper we assume that deployment

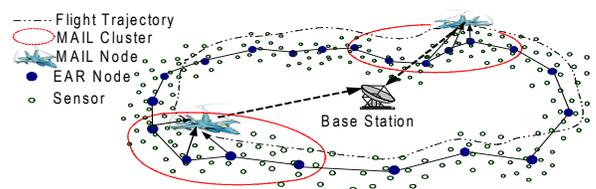


Figure 1: Hierarchical Sensor Network with Mobile Overlays.

and trajectories of each level of the network are given and we study how mobility in the *MAIL* level and multi-hop routing in the *EAR* level can affect the overall network performance.

Network Parameters and Definitions

Some of network parameters, notation, and their descriptions are provided in Table 1. Network lifetime is the duration of time before any of the sensor groups dies. This occurs when the sensors within the group fail to provide a minimum *QoM* or when the associated *EAR* node runs out of battery. In this paper, we focus on the *EAR* level of the network (issues related to sensor level failures fall outside the scope of the present work.) The overall *MoL* depends on network lifetime and lifetime of aerial vehicles.

Let *recurrence cycle* denote the time period for an *EAR* to be visited by two consecutive *MAILs* and *revisiting cycle* represent the time period for a particular *EAR* to be re-visited by the same *MAIL*. To obtain network lifetime, given the battery capacity of each *EAR* node, energy consumption during one recurrent cycle should be calculated. Energy consumption for wireless transmission is $\mathcal{E} = e_t d^\beta$ [8], where d is distance and e_t refers to energy dissipation for transmitting unit of data over unit of distance. Two-ray propagation model may be assumed for *EAR*-to-*EAR* communication, while *EAR*-to-*MAIL* communication may be assumed to follow the free-space model. Moreover, *MAIL* is typically equipped with higher gain antennas and thus e_t would be smaller for *EAR*-to-*MAIL* communication compared to communication between two *EAR* nodes.

III. ROUTING SCHEME

Without any delay and buffer size constraints, the optimal routing strategy for minimizing energy would be single-hop routing whereby an *EAR* node locally stores its data packets when it is outside the radio coverage of any *MAIL* and transmits its stored data when it is in the coverage region. However, due to latency and buffer size constraints and *MAIL* velocity limitations, and to avoid excessive packet losses, we propose a mobility-aware multi-hop routing scheme at the *EAR* level.

Each *MAIL* acts as a cluster-head for a set of *EAR* nodes. Due to mobility, *EAR* nodes within each cluster change over time. However, at any instance of time, each *EAR* belongs to only one cluster and forwards its data towards one *MAIL*. To select the routing path for a specific *EAR*, first a *MAIL* should be selected. Selecting closest *MAIL* clearly leads to less energy dissipation and less delay. *EAR* nodes form two chains around each *MAIL*. In one chain data packets are sent in the same direction as departing *MAIL* while in the other, data is forwarded toward the approaching *MAIL*. We call these chains *backward* and *forward* chains, respectively (cf. Figure 2). We find the closest *MAIL* based on the dynamic distance, which is measured in terms of the Dynamic Hop Count (*DHC*), that is, the actual number of hops

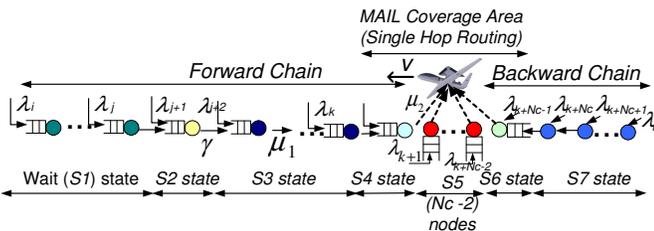


Figure 2: Cluster of *EAR* nodes, a *MAIL* node as a cluster head, link arrival and service rates, and state transition during recurrent cycle.

Table 1: Notations and their descriptions

	Description		Description
N	Number of <i>EAR</i> in network	M	Number of <i>MAILs</i>
λ_j	<i>EAR j</i> Aggregation Rate	E_0	Initial Energy of an <i>EAR</i> node
$1/\mu_1$	Avg. Link Delay for <i>EAR</i> -level	$1/\mu_2$	Avg. Link Delay for <i>EAR</i> - <i>MAIL</i>
β	Path Loss Exponent	e_t	Unit of Transmission Energy
E_M	<i>MAIL</i> Initial Energy	H	Hop Count Bound
v	<i>MAIL</i> Velocity	T_M	<i>MAIL</i> Recurrent Cycle
R_C	<i>MAIL</i> Coverage Distance	N_C	Avg. number of <i>EAR</i> nodes under <i>MAIL</i> Coverage
\bar{W}	Avg. Waiting Time in Queue		
C_M	<i>MAIL</i> Re-Charging Cost	C_{max}	Maximum cost for UAV service
D_{net}	Avg. Network Delay	D_{max}	Delay Constraint
T_{net}	Network Lifetime	T_{sys}	System Lifetime

needed to transfer data from an *EAR* to a *MAIL*. Note that due to mobility and routing delays associated with transmission, propagation and queuing, *DHC* differs from the Initial Hop Count (*IHC*) which is the number of hop counts that the *EAR* node will initially see at the starting time of transmission.

To minimize total energy consumption subject to latency and buffer size constraint, we propose a *Bounded Hop-count Routing (BHR)* strategy such that an *EAR* starts forwarding its data to a *MAIL* when it needs less than H actual hops for data transmission. Otherwise, it moves to a *wait state* and stores data until a *MAIL* becomes reachable again by H hops or less.

IV. SYSTEM ANALYSIS

We analyze *BHR* routing strategy to determine network delay, buffer size, and lifetime. Each *EAR* periodically experiences seven states based on *DHC* to closest *MAIL* (cf. Figure 2). Let $t_{link1} = \bar{W} + (1/\mu_1)$ be total delay due to communication and average waiting time in queue, and \bar{l} be the average distance that a *MAIL* travels between two *EARs*. Also note that *Recurrence cycle* time is the shortest period of time that a particular *EAR* node returns to any one of these states. By definition, a packet needs to be routed for (*DHC* -1) hops before reaching the single hop coverage area on the respective chain. It can thus be shown that *DHC* and *IHC* for forward and backward chains are related as:

$$(DHC - 1) = (IHC - 1) / (1 \pm \Gamma), \quad \Gamma \triangleq t_{link1} / \Delta t, \quad \Delta t \triangleq \bar{l} / v \quad (1)$$

A. Queuing Analysis

State definitions and transition times are presented in Table 2. Let Δt denote the average time needed for *MAIL* to fly the physical distance of one hop. Furthermore, after time Δt_f and Δt_b , *DHC* for an *EAR* changes one hop for forward and backward chains, respectively. Notice that the state transition time calculation considers the effect of queuing delays. Knowledge of the arrival, departure, and communication service rates of data packets in each state enables us to calculate queue size and subsequently calculate the average waiting time in each queue.

Let λ be the aggregate arrival rate of the packets from each group of sensors to their associated *EAR*. Furthermore, let μ_1 and μ_2 respectively be the service rates for *EAR*-level and *EAR* to *MAIL* links. Due to higher contention around a *MAIL*, longer time is typically required to access the channel for successful transmission of a packet to *MAIL* and hence $\mu_2 < \mu_1$.

For an *EAR* node i , $Q_i(t)$, $A_i(t)$, and $U_i(t)$ respectively denote queue size, arrival rate and departure rate to/from node i at time t .

Table 2: State definitions and state durations

State	Minimum Dynamic Hop Count (MDHC)	Status of receiving data from other sensors	States' Transition times $\Delta t \triangleq \bar{l}/v$, $\Gamma \triangleq t_{link1}/\Delta t$, $\Delta t_F \triangleq (1-\Gamma)\Delta t$, $\Delta t_B \triangleq (1+\Gamma)\Delta t$
S_1	$MDHC > H$	None.(on wait)	$T_1 = T_M - \sum_{i=2}^7 T_i$
S_2	$MDHC = H$	None	$T_2 = \Delta t_F$
S_3	$1 < MDHC < H$	Receiving	$T_3 = (H-2) \cdot \Delta t_F$
S_4	$MDHC = 1$	Receiving	$T_4 = \Delta t_F$
S_5	$MDHC = 1$	None	$T_5 = (N_e - 2) \cdot \Delta t$
S_6	$MDHC = 1$	Receiving	$T_6 = \Delta t_B$
S_7	$1 < MDH < H$	Receiving	$T_7 = (H-1) \cdot \Delta t_B$

Time reference, $t = 0$, is when node i enters state S_j . Graphs capturing sample time variations of $A_i(t)$, $U_i(t)$ and $Q_i(t)$ are provided in Figure 3. Note that these waveforms can change based on the relative values of H , λ , μ_1 , and μ_2 . For instance, as shown in Figure 3(c), there is no queue built-up in states S_6 and S_7 . This happens when $H\lambda < \mu_2 < \mu_1$.

The relation between $A_i(t)$, $U_i(t)$ and $Q_i(t)$ is as follows:

$$U_i(t) = \begin{cases} \mu_1 \text{ or } \mu_2 \text{ if } Q_i(t) > 0 \\ A_i(t) & \text{if } Q_i(t) = 0 \end{cases} \quad (\text{For } t > T_i) \text{ otherwise } U_i(t) = 0 \quad (2)$$

The transition points of the queue length curve, $Q_i(\cdot)$, are denoted by L_i and T_j denotes duration of time that node i spends in state S_i . From Little's theorem, the average waiting time at node i is $\bar{W}_i = \bar{Q}_i / \bar{A}_i$ and the average waiting time over all nodes would be \bar{W} . Given $\Gamma \triangleq t_{link1} / \Delta t$ and $t_{link1} = \bar{W} + (1 / \mu_1)$, we have a system of two equations for Γ and \bar{W} to obtain the average waiting time for a packet in each buffer.

Delay consists of the queuing and link delays. Therefore, for a network with average hop count, \bar{h} , the average end-to-end delay, D_{net} , can be calculated as:

$$D_{net} = \bar{h} \bar{W} + \frac{(\bar{h} - 1)}{\mu_1} + \frac{1}{\mu_2} \quad (3)$$

Using the above equation, D_{net} can be shown to be proportional to $1/(vH^2)$ and inversely proportional to the number of MAILs i.e. $D_{net} \propto (1/M)$.

Given the average DHC, average energy dissipation for routing packets can be obtained. Because energy model parameters of *EAR-to-EAR* and *EAR-to-MAIL* communications are assumed to be different, we separately calculate the average energy needed for data transfer to an *EAR* within coverage area, and the energy for sending a packet from that node to the *MAIL*. Let \bar{E} denotes the average energy dissipation for routing a packet and e_E and e_M respectively denote average energy consumptions for *EAR-to-EAR* and *EAR-to-MAIL* transmission. Hence,

$$\bar{E} = (\bar{h} - 1)e_E + e_M \quad (4)$$

where e_E and e_M respectively denote average energy

consumptions for *EAR-to-EAR* and *EAR-to-MAIL* transmission:

$$e_M = e_{12} R_C^{\beta_2}, \quad e_E = e_{11} \bar{d}^{\beta_1} \quad (5)$$

where \bar{d} is the average distance between two *EAR*s. Average number of packets generated during the lifetime of the network is equal to $N\lambda T_{net}$. Hence,

$$\bar{E} \cdot (N\lambda T_{net}) = NE_0 \Rightarrow T_{net} = E_0 / (\lambda \bar{E}) \quad (6)$$

It can be shown that the network lifetime, T_{net} (i.e., excluding *MAIL* endurance) is in fact independent of velocity and is inversely proportional to the square of maximum hop-count, i.e. $T_{net} \propto (1/H^2)$.

Another constraint is the size of the local buffer of each *EAR* node. When the internal queue size of a node, B_p , exceeds B_{max} , overflow occurs. Therefore, in order to avoid packet loss, the peak value of the queue size should be upper-bounded by B_{max} .

V. NETWORK OPTIMIZATION PROBLEM

We derived delay and network lifetime as functions of the network parameters, i.e., velocity and hop-count bound and *MAIL* coverage distance. For the *BHR* routing scheme these parameters should be optimally selected in order to maximize lifetime subject to delay, buffer size and *MAIL* recharging cost constraints.

The overall life time of system is $T_{sys} = \text{Min}(T_{net}, c \cdot T_e)$, where $T_e = \alpha E_M / (\rho v^3)$ is the aerial vehicle endurance time, ρ is air density and factor α depends on the fuel used for providing energy [9]. Also c is number of times a *MAIL* leaves for recharging. Hence, the optimization problem can be presented as:

$$\text{Max}_{v, H, R_C} \text{Min}(T_{net}, c \cdot T_e) \quad (7)$$

$$\text{s.t. } D_{net} \leq D_{max}, \quad B_p \leq B_{max}, \quad c \cdot C_M \leq C_{max}$$

To solve this Max-Min optimization problem, lets define $f = 1/T_{sys}$. Hence, based on definition of T_{sys} , $f \geq 1/T_{net}$ and $f \geq 1/cT_e$. Therefore the objective can be transformed into the following convex standard epigraph form:

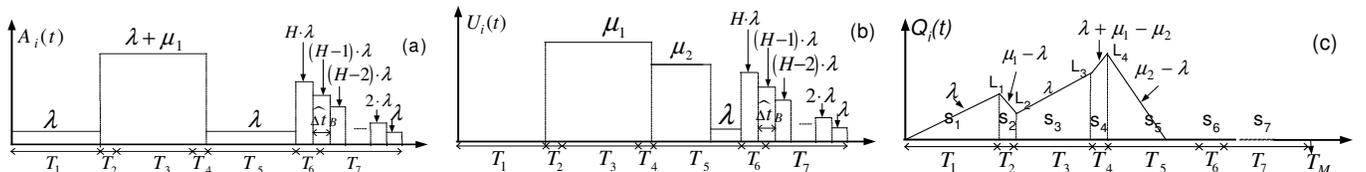
$$\text{Min}_{v, H, R_C} f \quad (8)$$

$$\text{s.t. } \lambda \bar{E} - f \cdot E \leq 0, \quad \rho \cdot v^3 - f \cdot c \cdot \alpha \cdot E_M \leq 0$$

The objective in (8) is linear. Furthermore, the constraints have linear or polynomial forms with positive coefficients with respect to the variables. One can thus prove the convexity of the optimization problem by showing that the second derivatives of constraints with respects to the variables are positive.

VI. SIMULATION PLATFORM AND RESULTS

We developed a sophisticated network simulator for the analysis of our network characteristics under the proposed mobility-aware bounded multi-hop routing scheme. While the system can be modeled as a network of G/G/1/K queues, we focused on D/D/1/K and M/M/1/K queues with vacation and variable service rates over the time. The simulations were performed for a sensor


 Figure 3: Temporal variations of (a) arrival rate, (b) departure rate, (c) queue size of an *EAR* node in a recurrence cycle.

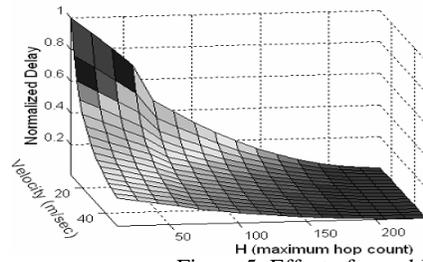
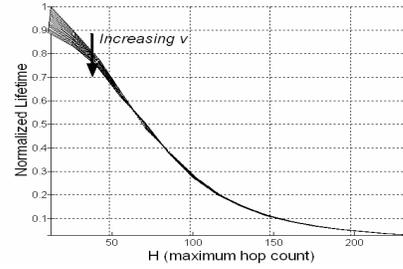


Figure 5: Effect of v and H on network delay and lifetime.



network with 100 *EAR* nodes randomly distributed on the borders of a closed area and two *MAILs* covering the overlay network. Path loss exponents follow free space and two ray models. Values of e_t for *EAR-to-EAR* and *EAR-to-MAIL* transmissions are 0.0013 and 10 (pJoul/bit/m²), respectively [8]. λ is set to 0.3 packets per second. We evaluated the effects of hop count bound, *MAIL* communication coverage area and its velocity, and validated our analytical results through simulations.

Figure 4 shows sample queue size variations. Also as shown in Figures 5, and 6, as the maximum bound on the number of hops, H , increases, both the network delay and the lifetime are reduced. This clearly indicates the trade-off between delay and lifetime. Note that increasing *MAIL* velocity could reduce the overall system lifetime due to shorter *MAIL* endurance time. *MAIL* single-hop coverage area has similar effects as the maximum hop count on delay and network lifetime. Larger coverage area means more data transmission to the *MAIL*, which in turn implies lower delay. The sudden changes in some points with respect to H are due to the characteristics of queuing backlogs.

VII. CONCLUSIONS

In this paper, a novel lifetime and delay aware deployment strategy for a hierarchical *WSN* is investigated. A mobility-aware multi-hop routing scheme is proposed and detailed analysis is conducted to characterize network lifetime, end-to-end delay, and buffer size. A packet level simulator is built to validate the analytical results. Effect of velocity and hop count bound on lifetime and delay are studied. This study shows that network delay is inversely proportional to the velocity of *MAILs*, whereas the effect of velocity on network lifetime is small. However, considering the mobile overlay, increasing velocity affects *Mol*. Moreover, our bounded dynamic hop count routing introduced a trade of between delay and lifetime witch can be controlled using the hop count bound. Note that in our scheme, we do not route data unless *DHC* is less than the hop count bound and thus selecting a feasible buffer size will avoid packet loss.

VIII. REFERENCES

[1] A. Iranli, M. Maleki, M. Pedram, "Energy efficient strategies for deployment of a two-level wireless sensor network," *Proc. of the International Symposium on Low Power Design (ISLPED)*, 2005.
 [2] Q. Li and D. Rus, "Sending messages to mobile users in

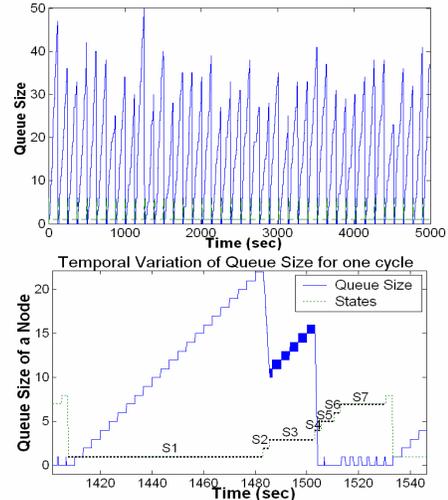


Figure 4: Simulated temporal queue size variation.

disconnected ad-hoc wireless networks," *Proc. of MobiCom*, 2000.

[3] R. Shah, S. Roy, S. Jain, and W. Brunette, "Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks," *IRS-TR-03-001*, Jan. 21, 2003.
 [4] S. Jain, R. C. Shah, G. Borriello, W. Brunette, and S. Roy, "Exploiting mobility for energy efficient data collection in sensor networks," *Proc. of Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, 2004.
 [5] W. Zhao, M. Ammar, and E. Zegura, "A message ferrying approach for data delivery in sparse mobile ad hoc networks," *Proc. of MobiHoc*, 2004.
 [6] A. Kansal, A. A. Somasundara, D. D. Jea, M. Srivastava, and D. Estrin, "Intelligent fluid infrastructure for embedded networks," *Proc. Of MobiSys*, 2004.
 [7] J. Luo and J.-P. Hubaux, "Joint mobility and routing for lifetime elongation in wireless sensor networks," *Proc. of the 24th Conference of the IEEE Communications Societies*, 2005.
 [8] W.R.Heinzelman, A.Chandrakasan, and H. Balakrishnan, "An Application-Specific Protocol Architectures for Wireless Networks," *IEEE Trans. On Wireless Communication*, vol. 1, no. 4, 2002.
 [9] Autonomous Vehicles in Support of Naval Operations, *National Academies Press*, <http://www.nap.edu/books/0309096766/html/200.html>.

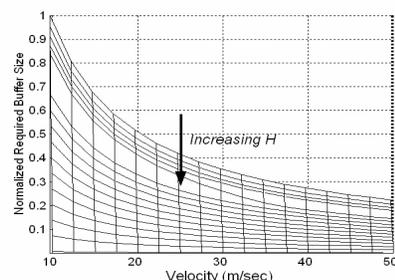


Figure 6: Effect of v and H on required buffer size.

