PERFORMANCE EVALUATION AND ENHANCEMENTS IN VIDEO SENSOR NETWORKS

by

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ABSTRACT

PERFORMANCE EVALUATION AND ENHANCEMENTS IN VIDEO SENSOR NETWORKS

Video Sensor Networks are developed with the aim of advancing the application performance of the traditional sensor networks and creating new applications. For instance, the reliability of surveillance applications is significantly improved with video streams captured from the events. Rather than detecting an intruder with traditional scalar sensors such as audio and magnetic, an image captured from the surveillance area offers a more detailed inspection of the event. However, for building a video sensor network, mounting CMOS cameras on top of the sensor nodes may not be sufficient. In this thesis, in order to clear up this matter, performance tests on the existing sensor network architectures are conducted by simulations designed for surveillance applications. The performance evaluations indicate that there is a need for enhancements in several layers of the OSI stack. Therefore, firstly, the fragmentation support of sensor MAC protocols which are designed for relaying large data units and data streams such as video are investigated. The improved application quality is observed with proper fragmentation support in terms of reduced latency and increased frame rates. The reason behind the improvements are discovered as the decreased control overhead and the adaptive duty cycle mechanisms.

Additionally, the fairness issue in the event based applications are investigated. In order to decrease the event reporting latency (mean response time) and to maximize the overall visual information, a fair queueing method based on the least attained service scheduling is proposed. The results indicate that the reporting delay is decreased and the minimum number of frames received from each event is increased. Also this mechanism is applied to multi-path schemes with variable contention windows.

ÖZET

VİDEO ALGILAYICI AĞLARDA BAŞARIM DEĞERLENDİRMELERİ VE İYİLEŞTİRMELER

Video algılayıcı ağlar geleneksel algılayıcı ağlar ile oluşturulmuş uygulamaların başarımlarını iyileştirmek ve yeni uygulama alanları yaratmak için geliştirilmiştir. Örnek olarak, bir gözetim uygulamasının güvenilirliliği olaylardan elde edilen video aktarımlarıyla önemli ölçüde artırılır. Ses ve manyetik alan ölçer gibi geleneksel algılayıcılar kullanarak yapılan hedef sezme yerine, gözetim alanından elde edilen bir imge daha detaylı inceleme yapabilmemizi sağlar. Fakat, bir video algılayıcı ağ oluşturmak için sadece düğümler üzerine takılan bir kamera yeterli olmayabilir. Bu tezde, varolan algılayıcı ağ mimarilerinde, gözetim uygulamaları için tasarlanmış benzetimlerle başarım testleri yaparak, eksiklikler açığa çıkarılmıştır. Başarım testleri sonucunda da OSI yığıtındaki birden çok katmanda iyileştirmelerin yapılması gerektiği ortaya çıkmıştır. Bu nedenle, ilk olarak algılayıcı ağlardaki ortam erişim kontrol protokollerinde büyük veri parçalarını ve video gibi veri akışlarını iletmede kullanılan parçalara ayırma yöntemleri incelenmiştir. Uygun parçalama desteğiyle uygulama başarısının, düşürülmüş gecikme ve artırılmış çerçeve hızı bakımından iyileştiği gözlemlenmiştir. İyileşmenin nedeni de kontrol amacıyla yapılan ek yüklerin azalması ve uyarlamalı uyuyup uyanma çevrimleri olarak tespit edilmiştir.

Ek olarak, olay tabanlı uygulamalarda adil kuyruklama konusu incelenmiştir. Olay raporlama gecikmesini azaltmak ve görsel bilgiyi artırmak amacıyla, en az alınan servis çizelgelemesine dayanan bir adil kuyruklama yöntemi önerilmiştir. Sonuçlar raporlanma zamanının düşürüldüğünü ve her olaydan alınan en az çerçeve sayısının artırıldığını göstermiştir. Ayrıca çokyollu yönlendirme yordamlarını kullanan sistemler üzerindeki etkileri de sınıflandırılmış çekişme penceresi boylarıyla denenmiştir.

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avg_q	Average queue length
CW	Contention window size
D_{AB}	Path length
f	Reporting frequency
F	Number of frames produced
H	Hop count from source
H_s	Minimum hop count from source to destination
$inst_q$	Instantaneous queue length
k	Number of factors
K	Camera frame rate
N	Number of contending nodes
r	Number of repetitions
R	Sensing radius
V	Target speed
w_q	Queue weight
α	FOV angle, Deviation angle
η	Normalized event reliability
Δ_E	Event inter-arrival time
Δ_F	Frame inter-arrival time
Ψ	Event size
ACK	Acknowledgement packet
AIMD	Additive Increase/Multiplicative Decrease
AMP	Adaptive Message Passing
B-MAC	Berkeley Medium Access Control
CDMA	Code Division Multiple Access
CMOS	Complementary Metal Oxide Semiconductor
CSMA/CA	Carrier Sense Multiple Access With Collision Avoidance

CTS	Clear to Send
DC	Duty Cycle
DCF	Distributed Coordination Function
DFI	Data Forwarding Interruption
DGR	Directional Geographical Routing
EBF	Event Based Fairness
ESRT	Event to Sink Reliable Transport
FB	Foreground Background
FCFS	First Come First Serve
FOV	Field of View
GPSR	Greedy Perimeter Stateless Routing
I2MR	Interference Minimized Multi-path Routing
LAS	Least Attained Service
LPL	Low Power Listening
MAC	Medium Access Control
MP	Message Passing
MTS	More To Send
OFDMA	Orthogonal Frequency-Division Multiple Access
OSI	Open Systems Interconnection
P-R-D	Power - Rate - Distortion
QoS	Quality of Service
RR	Round Robin
RTS	Ready to Send
SCFQ	Self - Clocked Fair Queueing
SIR	Signal to Interference Ratio
SMAC	Sensor Medium Access Control
SRPT	Shortest Remaining Processing Time
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TFP	Trespassers' Favorite Path
VSN	Video Sensor Network

VSSN	Video Surveillance Sensor Network
WMN	Wireless Mesh Networks
WMSN	Wireless Multimedia Sensor Networks
WSN	Wireless Sensor Network

1. INTRODUCTION

1.1. Video Sensor Networks

Tiny wireless sensor devices which are able to communicate in the wireless medium, sense and process the data build up the Wireless Sensor Networks (WSNs) [1]. Sensor networks are capable of gathering sensor readings such as temperature, humidity, light, acceleration, pressure, magnetic field. Beside the sensing task, sensor devices are desired to be self-organizing. With random deployment, they are required to sense the environment, discover their neighbors and relay the information gathered from the field to the decision centers called sinks. Each sensor can individually process and perform preliminary filters on the data, however hardware constraints such as processors at 13-416 Mhz, 32 MB available memory, lack of permanent energy supply [2], force them to operate collaboratively in large numbers. Additional to individual sensing, they are expected to cooperatively sense the area and aggregate the data according to the application specific requirements such as a temperature reading demanded for a region of the deployment area.

Since the energy is the most scarce resource and directly related to the network lifetime, novel energy saving techniques are required in order to prolong the network lifetime. For instance, sensors send their readings to the sinks employing a multi-hop communication pattern since multi-hopping saves energy in quadratic orders of the distance. Also sensor nodes are designed to dynamically power up and down the equipments to save energy. Especially the antenna part of the devices changes its power state in cycles called duty cycles (DC). Sensor nodes are expected to agree upon the duty cycle strategy and keep on networking without huge amounts of information losses.

In recent years, with the advances in CMOS cameras, availability of low-cost hardware and novel protocols, a new research field Wireless Multimedia Sensor Networks (WMSNs) [3] has emerged in WSNs. Basically, WMSNs are developed by upgrading the capacities of WSNs with low resolution cameras [4,5] and microphones. Beside the scalar sensor readings in traditional sensor networks, WMSNs can relay high bandwidth data such as video and audio streams, still images and use the same wireless architecture as WSNs. While the data sizes in WSNs are nearly 8 bytes (Double), WMSNs have to carry 10000 bytes every second. Therefore, the same problems in WSNs also exist in WMSNs and due to high bandwidth requirements additional constraints make the design of the network even more difficult.

A type of WMSNs is Video Sensor Networks (VSNs) which are multimedia sensors equipped with cameras. VSNs have the ability to generate and relay video streams. They introduce video to the sensor networks which emerge the need for application specific Quality of Service (QoS) requirements. Like in all other networks carrying multimedia content, in VSNs also expected latency, video quality and jitter are key performance metrics that need attention. Some foremost peculiarities are [3]:

- *Resource constraints:* As mentioned above, sensor nodes have limited capacity of processing, caching and bandwidth which are mandatory for video stream processing and relaying.
- *Variable channel capacity:* Differently from wired networks, in wireless networks, the channel capacity depends on the signal to interference ratio (SIR). In VSNs, the channel capacity vary among the nodes and regions on the network. For instance, if two video streams coincide on the network due to interleaving paths, they have to share the bandwidth. Even if there exists intelligent routing techniques that organize the paths, appearance of dead nodes makes interleaving paths inevitable.
- *Cross-layer coupling of functionalities:* In order to optimize the network performance, cross-layer protocols preferred in WSNs. When we try to obtain certain level of QoS for the streams, the interdependence between the network layers should be considered also.
- *Multimedia in-network processing:* In the literature considering multimedia processing, in general, as we have high processing power in the source that encodes and compresses the video and less processing power is needed in the destination

that decodes the stream. However, in sensor networks, the situation is vice-versa, we have low processing capabilities in the source and high processing power in the destination. Therefore, collaborative encoding and compressing algorithms on the network are required to handle the huge data streams.

Sensor networks are planned to be deployed in military [6, 7], habitat monitoring [8, 9], high quality and efficient agriculture [10–12], health [13–15] commercial [16, 17] and disaster monitoring [18, 19] applications. VSNs increase the reliability and precision in these applications and also create new applications. Among them, Video Surveillance Sensor Networks (VSSNs) are composed of video and acoustic sensors and aimed to be deployed in crime inspection, public event monitoring, border security and early warning systems for disasters [3, 20, 21]. The video capability in the surveillance networks enhances the traditional WSNs by [3]:

- *Enlarging the view:* Beside deploying less number of high resolution cameras, deploying many low resolution cameras increases the available view choices. Many tiny cameras means many images captured from the field compared to few detailed images captured by high resolution capable cameras.
- *Enhancing the view:* With dense deployments, cameras can view the same event from multiple perspectives. Though it can be considered as needless information or burden to the network, it increases the reliability of the applications.
- *Enabling multi-resolution views:* VSNs enables the idea of heterogenous multi-level camera architectures. When tiny cameras detect an event, high end cameras can zoom to the specific points and leverage the performance of the detection.

Among various application areas for video sensor networks, mainly VSSNs are considered in this thesis.

1.2. Motivation, Addressed Problems and Contributions

When compared with legacy WSNs that operate on scalar data such as humidity and temperature, the visual information provided by VSNs in general and Video

Surveillance Sensor Networks (VSSNs) in particular, increase the accuracy of event identification and decrease the false alarm rate considerably. However, this enhanced identification capability comes with the additional complexity of increased traffic volume that needs to be processed according to the realtime QoS requirements. Additionally, video traffic has its own metrics, data must be delivered with very short delays, for a successful delivery of frames either all or a large portion of the packets should arrive to the sink. Therefore, previously proposed WSN protocols may be insufficient for VSNs and there is a need for detailed analysis to reveal the congestion cases and bottlenecks of the network. With such a performance analysis using appropriate metrics, the operational region of the existing WSN architecture can be determined. For instance, video quality functions frames per second (fps), image size can be agreed upon and the effect of network parameters such as available memory on the metric latency can be observed.

As in other wireless environments, in VSNs, wireless communication errors due to environmental noise and packet collisions lead to packet errors frequently. In VSN and also in Wireless Sensor Networks (WSN), error correction techniques are rarely used in order to minimize redundancy. Instead, retransmission strategies are employed most of the time for reliable transmissions. However, when we consider retransmissions, the packet size plays an important role on the network performance. If small packets are preferred than the control overhead increases, if large packets are preferred than the retransmission delay increases.

In VSNs since the carried video traffic is composed of frames which are large data units, they are fragmented into smaller data packets. In the proposed MAC protocols which are mostly designed for traditional WSNs, those packets are treated individually. The protocol overheads such as RTS-CTS signaling are repeated for each packet of a frame. However in any sensor network design, the main goal should be minimizing the overheads that are waste of bandwidth and especially energy. Even if there are existing methods that are proposed to minimize the fragmentation overheads, their compatibility with VSNs are not investigated. Therefore, the existing protocols should be analyzed in order to make further optimizations on the fragmentation processes.

VSSNs are mostly configured to operate in event-triggered mode where nodes start pumping video frames as soon as they detect an event and continue to do so as long as the target is within the sensing radius and the Field of View (FoV). The number of frames triggered by an event is variable and as shown in Figure 1.1, it is a function of the duration of the event and the camera frame rate. Event duration is actually the target residence time inside the coverage area, which in turn depends on the target speed, V, and the path length, D_{AB}, covered inside the FoV.

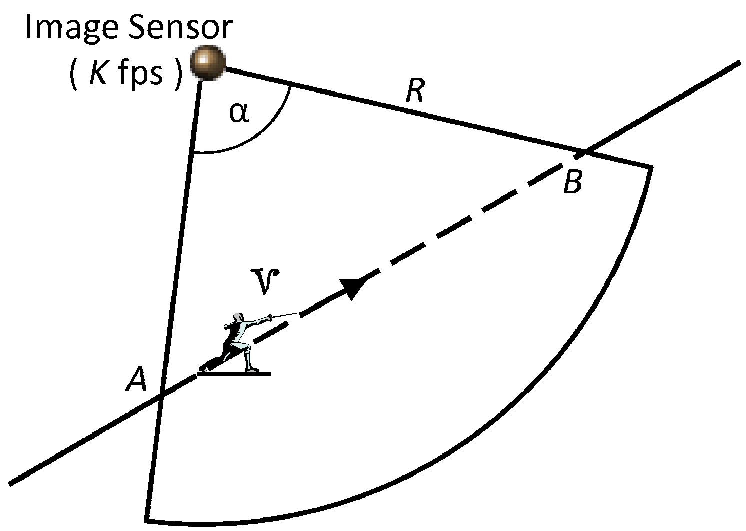


Figure 1.1. Number of frames F produced by a single sensor node upon detection is $F = K\frac{D_{AB}}{V}$ where K, V and D_{AB} stands for the camera frame rate, target speed and path length respectively. The path length D_{AB}, in turn, depends on the sensing radius R and the FoV, α.

An event-flow is identified as the sequence of image frames produced by the same source node triggered by the detection of a target. As opposed to the time-triggered (periodic) traffic pattern, for event-triggered traffic, the number of events created per unit time may easily reach high values depending on the number and mobility of the target(s). When combined with the large video frame sizes, this leads to instantaneous traffic volumes that exceeds the capacity of the network, which in turn results in packet drops due to buffer overflow.

As a result of lost traffic and congestion, the bandwidth assigned to the events can vary. Some events capture larger bandwidth and experience reduced delays compared to other events. In order to satisfy the fairness among the events, novel techniques which consider the variability in event size and constraints of the sensor nodes, need to be proposed and tested.

After defining the challenges in VSNs briefly, the addressed problems and contributions in this thesis are:

- Firstly, performance tests are performed in order to reveal the congestion cases and bottlenecks of the network. Surveillance application is chosen with constant number of targets in the network. A $2^k r$ factorial experiment set is designed, in which k is the number of factors, and r is the number of repetitions, for studying the effects of certain load shaping factors. These k factors are the number of targets, frame rate, buffer size, duty cycle and speed of targets (Chapter 2).
- Secondly, in order to investigate the fragmentation effect on video traffic Message Passing (MP) in SMAC [22] which is used for reducing *RTS-CTS* control overhead, is evaluated. Also as an improvement, Adaptive Message Passing (AMP) is proposed (Chapter 3).
- Thirdly, fairness among the events are handled. Two goals are satisfied, one is to maximize the overall visual information content conveyed to the sink in the presence of packet drops. The latter one is reducing the delay experienced by the initial frames of an event. To achieve these, an application level fairness scheme called *Event Based Fairness* (EBF) is introduced which is a scheduling scheme based on the Least Attained Service (LAS). Also an application level comparison is held against widely known First Come First Serve (FCFS) and Round Robin (RR) scheduling techniques (Chapter 4).
- Fourthly, like the previous item the fairness issue is investigated. However this time multi-path routing algorithms are incorporated and differentiated contention window sizes are applied to the frames of events according to their sequence numbers (Chapter 5).

1.3. Literature Review

In the literature, there are studies that evaluate the performance of the VSNs. Most of them focus on the energy consumption. Video compression is shown to be a must in VSN because of its impact on the energy consumption [23]. Additionally, it is noted that the delay of the video stream stem from not only network latency but also the processing time of the video. Even the main delay source can be compression if the processing power of the sensor device is not sufficient. Furthermore, the authors emphasize that although compression algorithms has significant effect on data reduction, the distortion introduced can result in poor application performance. Therefore, all these factors should be taken into account for better network and application performances.

Resource utilization behavior of VSN was investigated under resource constraints [24]. In this work, authors employ an analytic power-rate-distortion (P-R-D) model to find out the relationship between the power consumption of a video encoder and its rate-distortion performance. Additionally, there are studies that involve performance investigation of WSNs. These studies give us hints about the behavior of the VSNs. WSNs energy consumption is modeled with Markov chains [25]. Authors design the model considering a widely known energy saving technique, sleep schedules. With sleep schedules the nodes enter in low-power state while reducing their communication and sensing capabilities. Authors construct a model involving: "(i) the behavior of a single sensor. (ii) the dynamics of the entire network. and (iii) the channel contention among interfering sensors". Also the accuracy of the analytical model is shown as matching with simulation results. The performance of S-MAC [22] protocol is investigated which is widely used as a WSN MAC protocol [26, 27]. IEEE *802.11*, IEEE *802.15.4* and S-MAC are compared by simulations [26]. Authors determines four performance metrics:

(i) *Packet Delivery Ratio*: The ratio of delivered packets to generated packets. Constant Bit Rate traffic shape is preferred for traffic generation.

(ii) *Average packet latency*: Time between sending the packet from source and receiving the packet at the destination.

(iii) *RTS/CTS overhead*: The ratio of RTS/CTS control packets to data packets.

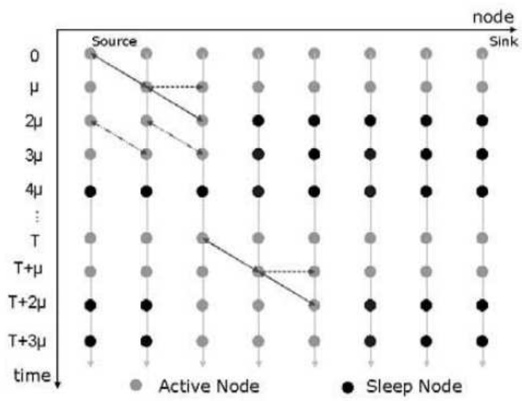
(iv) *Energy consumption*: Since the main aim of a sensor MAC is reducing the energy consumption, the average energy consumption on the network is also added as a performance metric.

In the results, authors observe that packet delivery ratio and average latency metrics are better in *802.11*, however the energy consumption is higher than the others. The minimum energy consumption is observed in SMAC. It is also noted that in high traffic load the RTS/CTS overhead is less in SMAC with respect to *802.11*. Authors discover that SMAC is suitable for delay tolerant applications; however, for energy-conservation and latency performance, they choose IEEE *802.15.4*. SMAC performance is evaluated with analysis [27]. However, authors only consider single-hop WSNs.

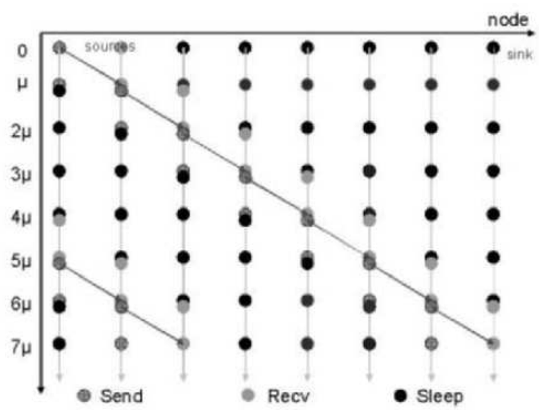
In sensor networks and also in other networks, retransmission and error correction techniques are used to set up a reliable communication in case of transmission errors and packet collisions. If the retransmitted packet is long and a few bits have corrupted than the network encounters a big delay in each retransmission. In order to eliminate the penalty of long retransmission delays, fragmentation is employed in networks. However, in fragmentation, the size of the fragmented units has a significant effect on the goodput of the network. If small packets are preferred than the control overhead such as RTS/CTS messaging before each packet increases.

The performance of IEEE 802.15.4 was evaluated [28]; in this work, authors study the effects of "Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA) mechanism, variable number of network devices, sampling rates and transmitting cycles". They choose transmission delay, latency and packet delivery rate as performance metrics. They conclude that large packets increase the delivery rate with high channel efficiency with certain number of sensors. However, the delivery rate in dense networks is lower due to large number of competing nodes. The authors also indicate that the end to end latency increases with larger packets.

Authors propose DMAC which aims to optimize the data delivery in data gathering trees in WSNs [29]. They introduce the data forwarding interruption problem (DFI). In a network, future relay nodes that do not overhear the packets between the sender and the receiver keep on its sleep/awake cycle since they are unaware of incoming packets directed to them. When the data packet reaches to the future relay node, the data forwarding process is interrupted and the sender waits for the node to enter in awake state. Meanwhile the sender node may encounter buffer restrictions and starts dropping the packets or the latency of the packets increases so high that the packet becomes worthless for the application.



(a) SMAC



(b) DMAC

Figure 1.2. (a)DFI causes sleep delay. (b)DMAC reduces sleep delay [29]

As depicted in Figure 1.2 [29], DMAC solves the DFI problem and it employs two methods to overcome the problem. Firstly, a *more data flag* is piggybacked in the MAC header in order to prevent the receiver to enter in sleep state. The receiver extends its active period with this message. Thus a data stream or fragmented parts of a large packet are relayed with reduced latency. Secondly, a More To Send (MTS) packet is send when interference exists in the network. For instance A and B are in the same interference range. When A wins the contention, B cannot send its packet to C in that slot, therefore B sends an MTS packet which has a destination field and a bit (1/0) indicating there is a packet waiting to be transmitted or not. When C captures the MTS it keeps waking up periodically every 3μ and at the end of A's transmission B can send its packet immediately to C.

Berkeley Medium Access Control (B-MAC) is proposed and in B-MAC a periodic channel sampling called Low Power Listening (LPL) is used to duty cycle the radio [30]. Since LPL creates an overhead, it is removed in fragmented messages. In the first fragment LPL is enabled, and the number of subsequent fragments is sent to the receiver, then at the following fragments LPL is disabled. Thus the energy per byte is decreased significantly. In SMAC, a fragmentation method called Message Passing (MP) is proposed in order to decrease the use of RTS/CTS messages [22]. The frame is fragmented into packets then sent in bursts. RTS/CTS messaging is done only before the first packet. The rest of the packets are sent after getting the ACK message of the previous packet. Later in Chapter 3, MP will be described in detail.

The fragmentation of the packets is an active issue also in other domains. The effect of introducing large TCP frames to the networks is examined [31]. The authors claim that the abundance of small ACK packets in the TCP networks reduces the network performance, and by employing large frames we can decrease the number of small packets and their ACK packets. However it is also noted that the drop rates of the large frames is higher than small ones due to limited buffer spaces. Authors try to find a solution for multi user frame aggregation in OFDMA based wireless local area networks [32]. A frame aggregation technique is proposed for 802.11n networks which can co-exist with legacy systems.

Fairness is well-studied in the context of wired networks [33–35]. For wireless communication, fairness is generally discussed according to the OSI level that fairness is supported. For instance, authors of [36] advocates that MAC level fairness alone cannot ensure the fairness of the whole wireless network, although MAC support can increase the efficiency for the fairness provided at the network layer. An option to make the network independent of the fairness issues at lower layers is to achieve fairness at the transport flow layer. A centralized max-min fairness approach for wireless mesh networks (WMN) which strives to achieve end-to-end fairness at the transport layer is presented in a work [37]. The centralized solution discussed is justified for WMNs but it is not applicable for the WSN case whether it be a scalar or a video based WSN.

There are studies that specifically address fairness in WSNs [38–40], among which Rangwala et al. proposes IFRC that combines fair bandwidth allocation with rate control [38]. The average queue length which is computed by an exponentially weighted moving average of instantaneous queue length: $avg_q = (1 - w_q) \times avg_q + w_q \times inst_q$, is selected as the metric for congestion detection. When a congestion is detected additive increase/multiplicative-decrease (AIMD) algorithm is applied to ensure the fairness among the flows. Authors deal with the rate adaptation for rechargeable sensor networks that are aimed to be deployed in habitat monitoring [39] (Figure 1.3). They describe their objective as "to design a solution for fair and high throughput data extraction from all the nodes in the network in the presence of renewable energy sources". Also the rate assignment criteria is defined as lexicographically maximum, in other words increasing the rate of a node should not lead to a decrease in nodes with lower rates. Two methods are proposed for the optimal rate assignment. Firstly, a centralized algorithm which computes the optimal rate for each flow on the links is proposed, then a distributed version which also finds the optimal rate distribution when the routing tree is predetermined.

Feedback based congestion control mechanisms to enhance data delivery such as ESRT, CODA and SPEED [41–43] are classified as reactive and the authors come up with a collision-free scheduling that provides max-min fairness in a proactive and distributed manner [44]. In that sense, our work in Chapter 4 also can be characterized as proactive. Unlike the VSSNs, authors focus on applications with predictable and stable traffic flows and try to solve the the fairness issue by a linear programming

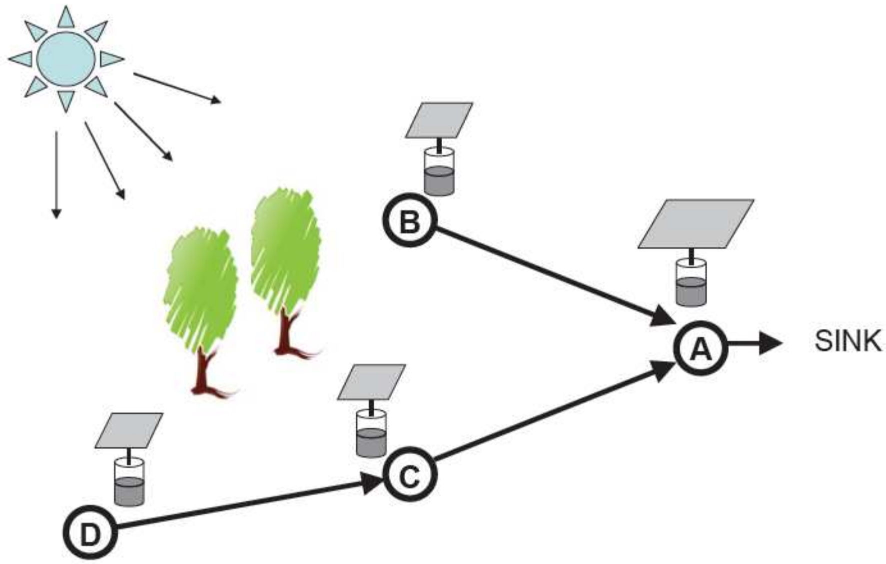


Figure 1.3. A network with four nodes, each equipped with a solar cell and a rechargeable battery [39]

approach [44]. A similar work by Tassiulas et al. proposes a scheduling scheme which achieves max-min fairness without giving the implementation level details of the MAC protocol [45]. Authors gives a brief definition of the max-min fairness as "a bandwidth allocation is max-min fair if and only if every flow satisfies at least one of the following conditions: (a)the flow has at least one bottleneck node (b)the bandwidth allocated to the flow equals its long term arrival rate". A policy is described in order to satisfy max-min fairness. The stages of the policy are as follows:

(i) A round-robin token service system is deployed on the nodes for each traffic flow traversing the node.
(ii) Each flow has two service token buckets one for the sender and one for the receiver. The credit score of the flow is determined as the minimum of two token buckets.
(iii) The weight of each flow is defined as its service credit and a maximum weighted matching of the flows is scheduled for transmission.
(iv) One token is captured in each service of the flow from its token buckets.

Vaidya et al. proposes a variant of *IEEE* 802.11 DCF MAC protocol which incorporates Self-Clocked Fair Queueing (SCFQ) [46] to achieve max-min fairness in a distributed manner [47]. Using the *backoff interval* mechanism from 802.11 the prioritization of the flows are accomplished. Simply, the length of the backoff interval is determined as proportional to the finish tag of the packet to be transmitted.

Among feedback based mechanisms, ESRT [41] is a transport protocol designed to guarantee the reliable event delivery and reduce the energy consumption. The designed protocol tries to carry the optimum number of packets from an event with a feedback mechanism from the sink to the nodes. However, the effectiveness of ESRT depends on the length of decision intervals ($\approx$ 10 sec) and the feedback latency. If the duration of the event is short as in surveillance applications and the feedback latency is high (e.g., the network diameter is high), the notification may arrive to the source after the end of the event and cannot avoid congestion. Therefore, the protocol cannot be able to avoid the congestion. Moreover, ESRT is not designed to decrease the reporting delay of the events.

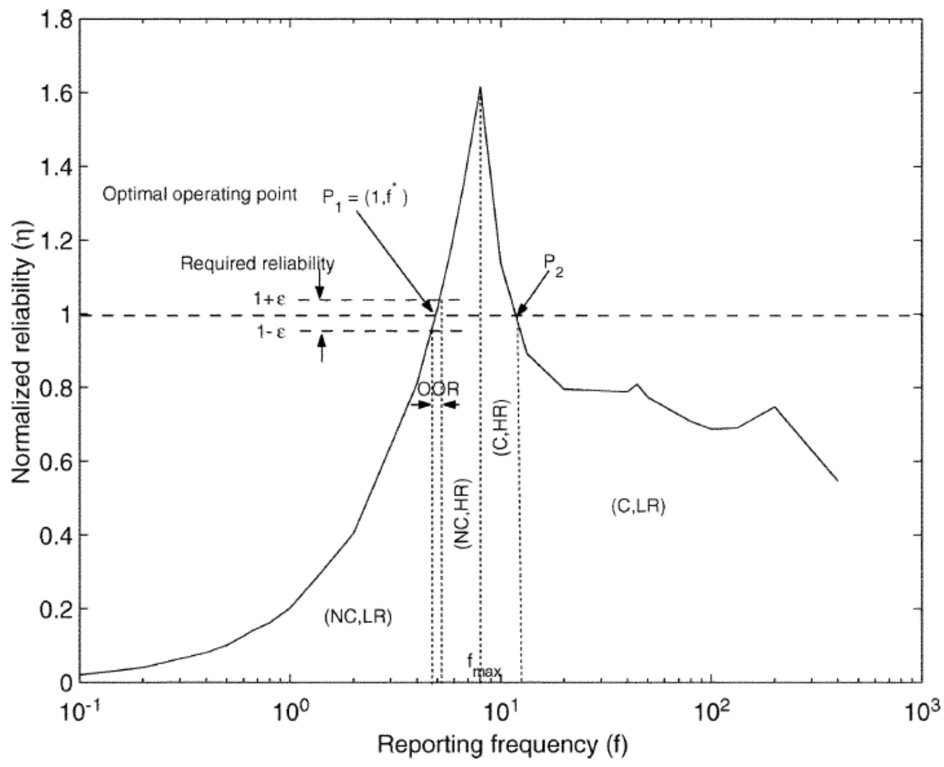


Figure 1.4. The five characteristic regions in the normalized event reliability η versus reporting frequency f behavior [41]

In ESRT, the optimal operating point of the application is tried to be sustained. As depicted in Figure 1.4 [41], application performance is divided into five regions, each region is characterized by the event reporting frequency in the source and the reliability measure of the event at the application level. As discussed above, the sink tries to fix the network performance near the optimal region by sending increase frequency or decrease frequency messages directly to the traffic sources.

- (NC,LR): $f < f_{max}$ and $\eta < 1 - \epsilon$ (No Congestion, Low Reliability)
- (NC,HR): $f \leq f_{max}$ and $\eta > 1 + \epsilon$ (No Congestion, High Reliability)
- (C,HR): $f > f_{max}$ and $\eta > 1$ (Congestion, High Reliability)
- (C,LR): $f > f_{max}$ and $\eta \leq 1$ (Congestion, Low Reliability)
- (OOR): $f < f_{max}$ and $1 - \epsilon \leq \eta \leq 1 + \epsilon$ (Optimal Operation Region)

As mentioned in a recent survey on the *Least-Attained Service* (LAS) [48], the *Shortest Remaining Processing Time* (SRPT) is optimal for minimizing the mean response time. SRPT gives precedence to the jobs with the shortest remaining time left by assuming that the queue dispatcher is aware of the residual size of the job that has not arrived yet. However, in *blind* systems as in WSNs, although the length of the flow may not be known, a job's age is always known, therefore instead of SRPT, a more practical policy, LAS scheduling is a better choice. In the literature, LAS scheduling exists with different names, such as *Foreground-Background* and *Shortest-Elapsed-Time* [48]. Among them, the performance of LAS with respect to the variability of the job size is analyzed [49]. Authors indicate that while 99 per cent of the jobs encounter a reduced conditional mean slowdown under LAS, less than 1 per cent of the largest jobs experience a negligible increase of their conditional mean slow down. Wierman et al. showed that LAS outperforms *Processor-Sharing* with respect to the mean response time and the mean slowdown when the job size distribution has a decreasing failure rate [50]. Furthermore, Wierman et al. present a classification of scheduling policies considering the unfairness in [51]. Furthermore, the effect of LAS on heavy-tailed traffic in wireless networks is presented [52]. The authors compare LAS with *Round-Robin* (RR) based scheduling and show that LAS outperforms RR in a single bottleneck link and also in a one hop wireless shared link.

In sensor networks the deployments are done in excessive amounts, many sensor nodes are deployed to the sensed area close to each other. Therefore, the number of the neighbors for a sensor node is large enough to select different relay nodes for the traffic. In the literature, mostly single path approaches are deployed which incorporate some metrics such as hop count, distance to sink, energy of the relay nodes, buffer space in the nodes. Although the optimum path is established according to the metrics, it can be infeasible due to the network topology changes caused by dead nodes, which forces to discover new paths on the network. Also, because of temporary congestion cases and high interference, the packets can be lost on the path. Moreover, in single path algorithms, the available bandwidth of the network is not utilized totally. Taking all into consideration, employing multi-path routing algorithms is a better choice in order to improve the reliability and throughput.

Directional Geographic Routing (DGR) [53] is a multi-path routing algorithm designed to relay realtime video communications. Like Greedy Perimeter Stateless Routing (GPSR) [54], DGR chooses the relay nodes according to the distance of the neighbor nodes to the sink. However, in DGR relay nodes are logically mapped to new locations by rotating according to a predefined deviation angle. The closest relay node to the sink is chosen among the mapped locations. In the extreme case when the angle is set to zero, DGR behaves like GPSR. In Figure 1.5, some disjoint paths with different deviation angles are depicted. It should also be noted that the deviation angle converges to zero by applying an adjusting function. Denoting the hop count from source as H and the minimum possible hop count from source to sink as H_s, some adjusting functions are given as $(\frac{\max[0, H_s - H]}{H_s}) \cdot \alpha$, $(\frac{\max[0, H_s - H]}{H_s})^2 \cdot \alpha$ and $(\frac{\max[0, H_s - H]}{H_s})^3 \cdot \alpha$. The power of the function determines the convergence rate of the angle to zero.

Authors argue that in wireless sensor networks with high rate traffic, multi-path routing algorithms are required [55]. However, the authors claim that establishing node-disjoint paths is not sufficient due to route coupling problem which is defined as the interference between the different paths on the network. When the paths interfere with each other, they cannot transmit the data in a parallel way. Therefore, zone-disjoint shortest paths are tried to be established by a heuristics-based protocol called

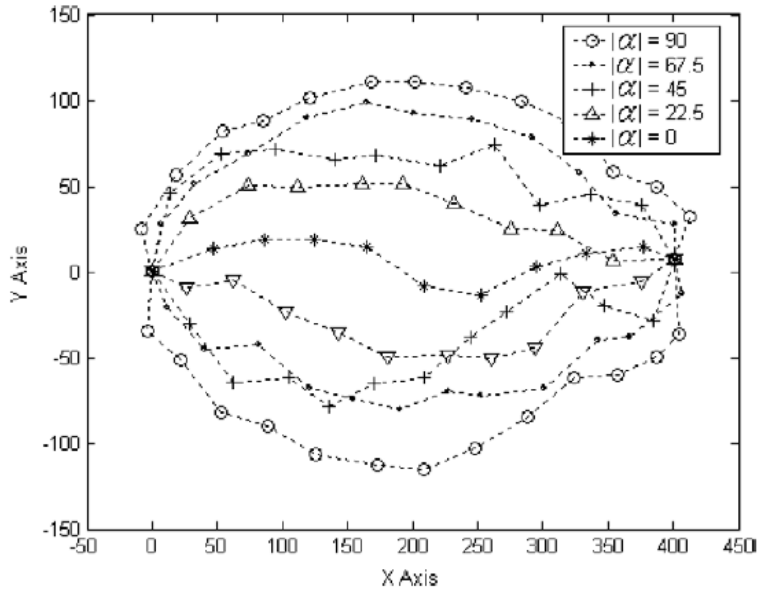


Figure 1.5. Example of nine disjointed paths using DGR [53]

Interference-Minimized Multi-path Routing (I2MR) [55]. Furthermore, it is stated that only source nodes require localization support which are more powerful than the relay nodes. Additionally, a congestion control scheme for load balancing among the nodes is proposed.

In CSMA based MAC protocols, the nodes capture the medium by contending for it. In a predefined contention window with slots, the node chooses one of them mostly in a uniform distributed fashion and sends its control packet indicating the request. If two or more nodes choose the same slot, collision occurs and back-off algorithms are employed in order to resolve packet loss. As stated previously, sensors are deployed in large volumes in order to increase coverage, reliability and decrease energy consumption which results in many sensor nodes contending for the medium at the same time. Since the probability of collision increases with the number of contending nodes, suitable contention window sizes or other techniques which minimize the number of collisions are proposed in the literature.

The size of the contention window is determined as a function of contending nodes aiming energy and delay optimization [56]. Also a method for estimating the number of contending nodes is presented. A hashing back-off method to figure out collision free slots for each sensor node is proposed [57]. The authors state that the proposed method is half-way between TDMA, CDMA and random access. The method does not depend on N, the number of contending nodes and it finds out orthogonal back-off sequences to attain a collision free schedule.

Although changing the properties of contention window for collision free access has great importance, prioritization among the packets of flows can also be achieved by dynamic contention windows. Prioritization to real time flows are given with smaller contention window sizes with respect to the best effort traffic in 802.11 Distributed Coordination Function (DCF) [58]. The contention window size CW is arranged such that $CW_{min,RT} < CW_{min,BE}$ and $CW_{max,RT} = CW_{max,BE}$, which means that overlapping contention windows are deployed. In Chapter 5, instead of overlapping contention windows, differentiated contention windows where $CW_{max,RT} < CW_{max,BE}$ are employed for inter-node fairness.

2. PERFORMANCE EVALUATION OF VIDEO SURVEILLANCE SENSOR NETWORKS

In this chapter, the effects of network parameters on the performance of the VSSNs are explored. Moreover, congestion cases and bottleneck resources are identified.

2.1. System Model

We use the OPNET simulation environment [59] for the performance tests. Since there are no available modules for VSN, we have implemented the SMAC [22] and GPSR [54] protocols as the underlying MAC and routing protocols, respectively. The sink is placed to the center of the deployment area where the sensor nodes are deployed uniformly in a random fashion. All the nodes are capable of taking images and compressing them with the cameras integrated on their hardware [60, 61]. Since the size of the data transmitted is directly related to the size of the image, SQCIF (128×96) format is assumed. The image module employs intra-frame encoding which results in compressed images of size 10 Kbits. Predictive encoding alternatives such as ISO MPEG and H.26x cannot practically be used in VSNs due to the high complexity involved [3]. Distributed source coding techniques are promising alternatives for encoding video in VSNs as they exploit the inter-frame redundancy with affordable complexity in the sensor nodes [62]. However, due to the lack of practical implementations yet available, we resort to the JPEG compression available on the image module. Software controlled frame rate feature allows capturing the video with rates $1-12$ fps. Event triggered data generation is simulated where the triggering event is the visual detection of a target. Since the cameras equipped, support background subtraction feature, they only produce an image when the scenery changes significantly. Hence triggering occurs when the target is within the camera detection range of 30 m and is within the Field of View (FOV) of 52 degrees. The target is assumed to move in the surveillance area according to the Random Waypoint Mobility Model where the target speed is a simulation parameter and the pause time is set to 0 seconds. The crucial simulation parameters and the factors investigated are tabulated in Table 2.1 and Table 2.2, respectively.

Table 2.1. Simulation Parameters

Parameter	**Value**
Simulation tool	OPNET
Surveillance area	400×400 m^2
Number of sensors	100 nodes
Deployment type	Uniform random
Video frame size	10 kbits
Packet size	1 kbits
Camera detection range	30 m
Field of view	52 degrees
Target mobility model	Random Waypoint
Bandwidth	250 kbps

We designed expreiments according to the $2^k r$ *factorial design* [63]. This experimental design is used to determine the effect of k factors, each of which has two alternatives or levels. We investigate five factors which are described in Table 2.2 and in order to diminish the experimental errors, we run each simulation r = 8 times. In our case, we run 2^5 x 8 = 256 factor sets. For each set, we simulated four hours of network operation where the statistics of the first 30 minutes is discarded for a better steady state analysis. In order to identify the effects of the factors, we use the performance metrics in Table 2.3. The metric *Dropped frames/packets on way* describe the frames or packets that are dropped at the relay nodes. We include both the frame and packet related metrics to the analysis since in early observations, we observed that they can behave differently.

Table 2.2. Investigated Network Factors

Factor	**Value**
Buffer size	$20, 200$ Kbits
Duty cycles	$5, 50$ per cent
Speed of targets	$1, 10$ m/s
Camera frame rate	$1, 10$ fps
Number of targets	$1, 5$

2.2. Analysis of the Simulation Results

After gathering the data, we apply the allocation of variation technique as described in [63]. We present percentage of the effect of a factor on the metric with respect to others in Figures 2.1 through 2.8. The variances on the results of the metrics are presented as error bars.

In the figures, the individual effect of each factor is presented. Also, the cumulative effects of the factors are added to figures, however because of the limited space only prominent ones are included.

Figure 2.1 indicates that the duty cycle, buffer size and speed of the targets do not have much effect on the traffic load. Obviously the reason is that they do not have any effect on the sensing unit. However, we should notice that in our duty cycle mechanism, only the radio unit which dissipates more energy than the sensing unit, goes into sleep state periodically. Additionally, besides increasing the frame rate and the number of targets individually, increasing both has a multiplicative increase on the traffic generation.

Figure 2.2 and Figure 2.3 show us the reason behind the drops at the source. In both graphs, the frame rate and the number of targets have the most significant effect

Table 2.3. Performance Metrics

Performance Metric
Created frames per second
Dropped packets on way per second
Dropped frames on way per second
Dropped packets at source per second
Dropped frames at source per second
Received frames at sink per second
Received packets at sink per second
Average latency

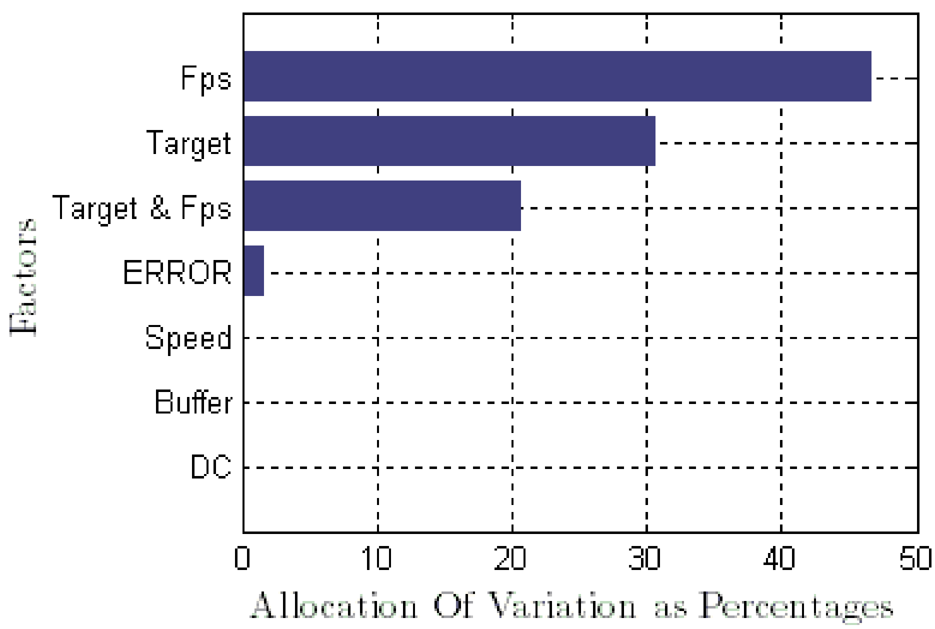


Figure 2.1. Effects of the factors on the number of frames created per second

since increasing them directly increases the created traffic as seen in Figure 2.1. The other factors in Figure 2.2 and Figure 2.3 also have effects on the frame/packet drops. The main difference between the figures is the effect of buffer size and DC. After a frame is generated by the video camera, if there is no available space left in the buffer, it is dropped immediately. Therefore, the buffer size plays an important role in frame drops. On the other hand, since the packets are individually sent to the network, the packets are closely related with the DC. Another point that should be argued is that the effects of the buffer and the duty cycle are lower than the expected. The reason is that although we increase the buffer 10 times, it is still not enough to handle that much traffic. Moreover, since the total bandwidth is not sufficient for highly loaded video traffic, the effect in decreasing it with the duty cycle cannot be observed.

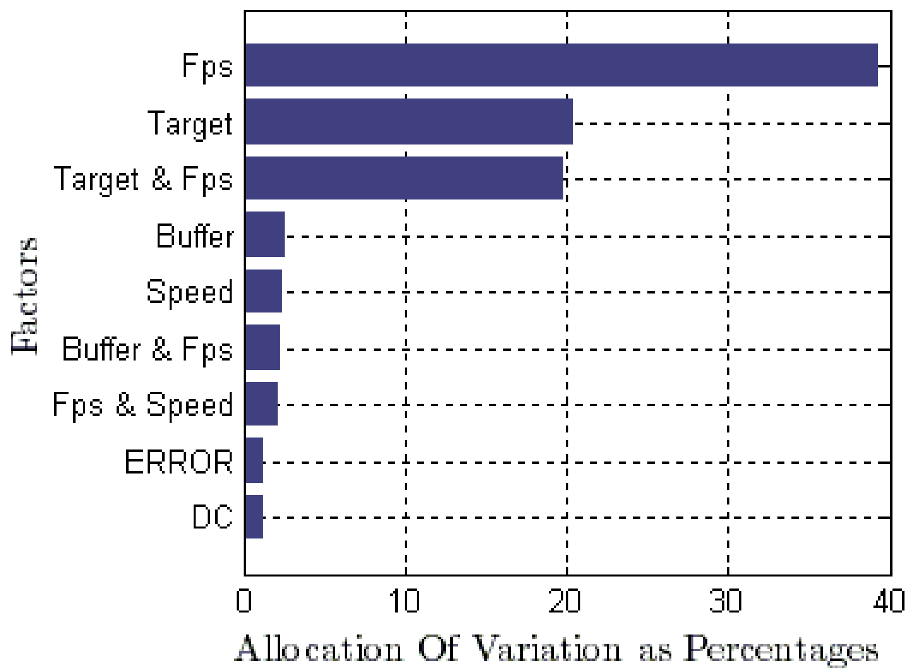


Figure 2.2. Effects of the factors on the number of frames dropped at source per second

Figure 2.4 and Figure 2.5 basically indicate the factors that lead to congestion. Again the frame rate and the number of targets have the most significant effect, since they increase the load in the network. Moreover, the speed of the targets has a crucial effect on the drop counts. When we increase the speed of the targets, the dwell time decreases which results in a decrease on the number of frames generated by the nodes. However, the cumulative traffic on the network remains nearly the same, since the number of nodes that generate traffic increases. Namely, while the traffic generated by one node decreases, the number of nodes that detect the target, hence that generated traffic increases. When multiple neighboring nodes generate traffic simultaneously, the congestion in the network increases as well as the frame/packet drops on the way.

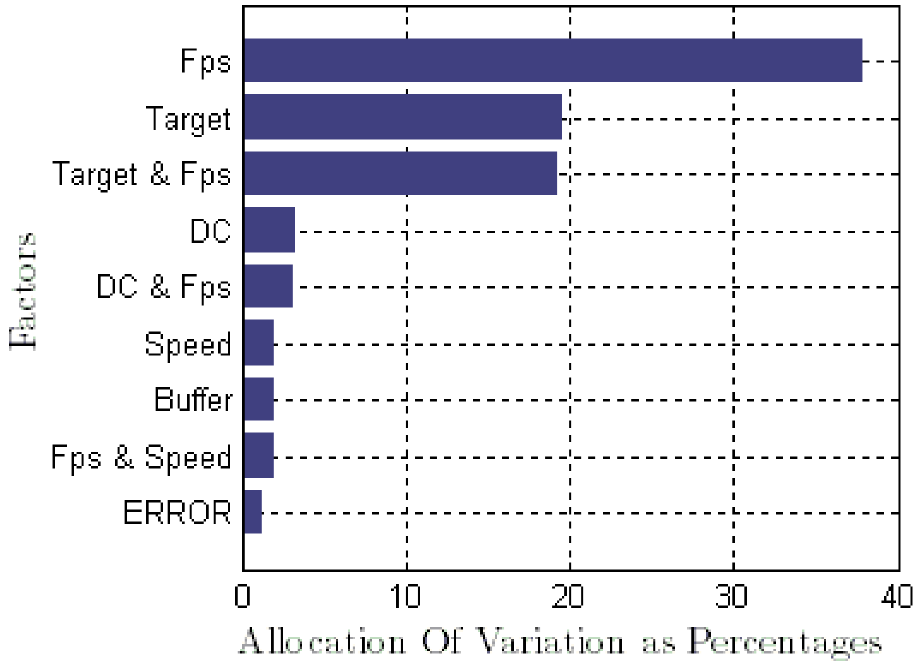


Figure 2.3. Effects of the factors on the number of packets dropped at source per second

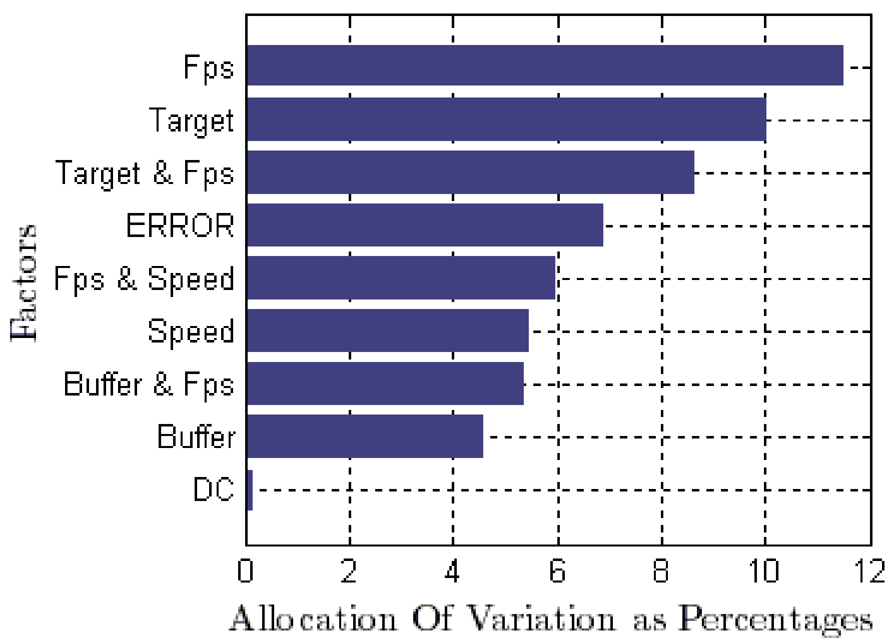


Figure 2.4. Effects of the factors on the number of frames dropped on way per second

The increase in buffer size increases the latency of frames as seen in Figure 2.6. Besides, increase in DC decreases the latency. Although the DC has negligible effects

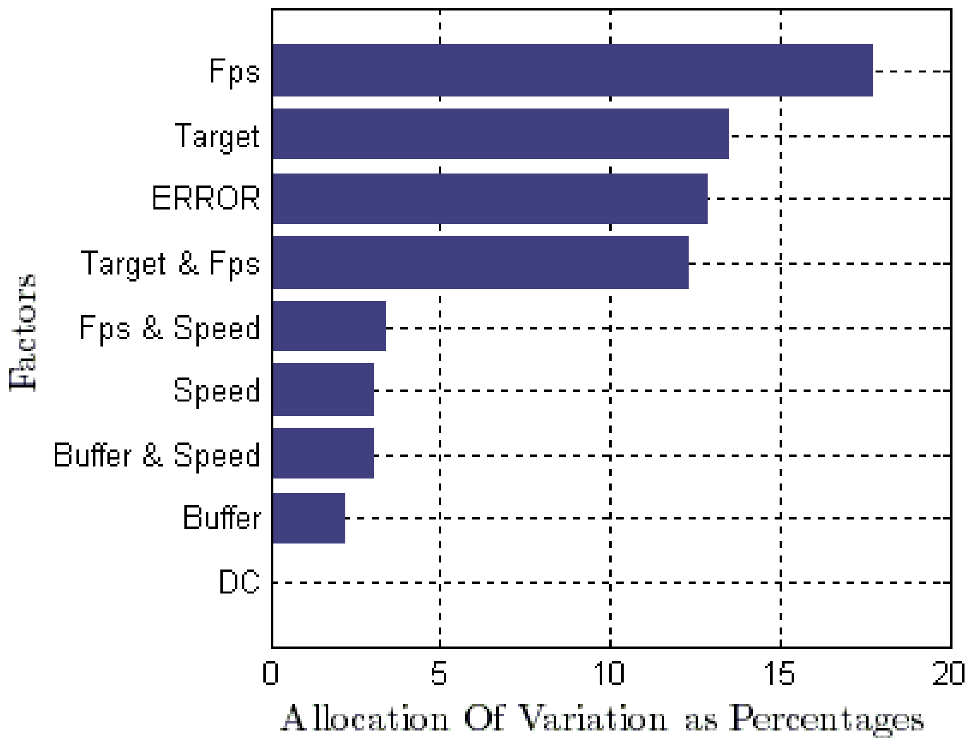


Figure 2.5. Effects of the factors on the number of packets dropped on way per second

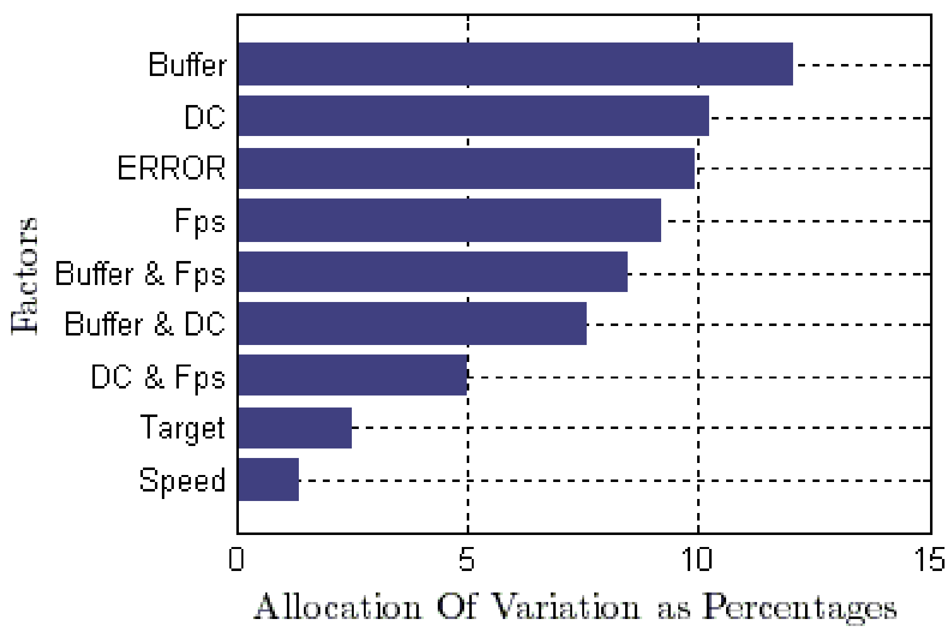


Figure 2.6. Effects of the factors on average latency

on the previous metrics, it is a crucial parameter for the average latency. Hence, for the time critical applications, the DC parameter should be set carefully.

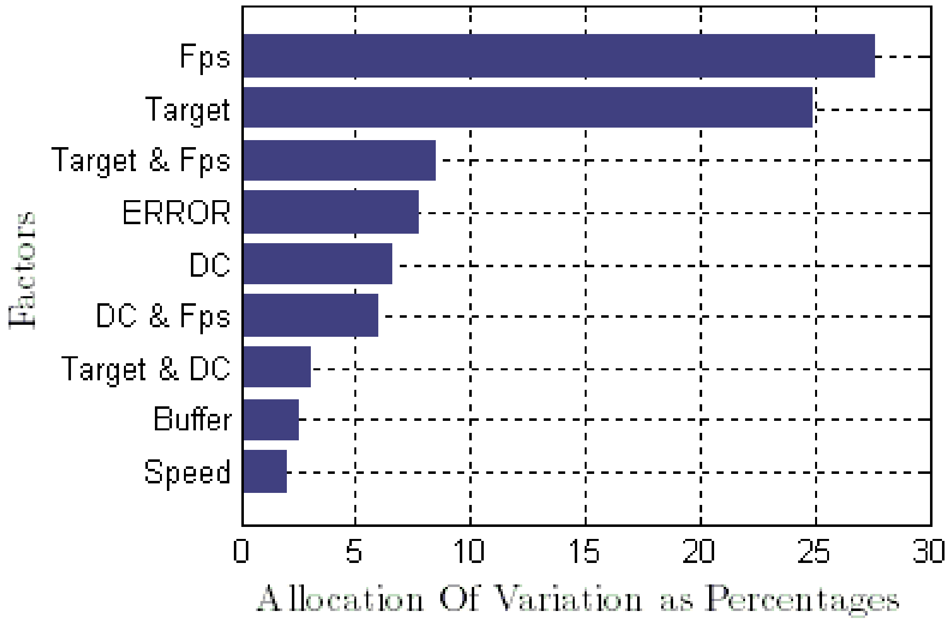


Figure 2.7. Effects of the system parameters on the number of packets received at sink

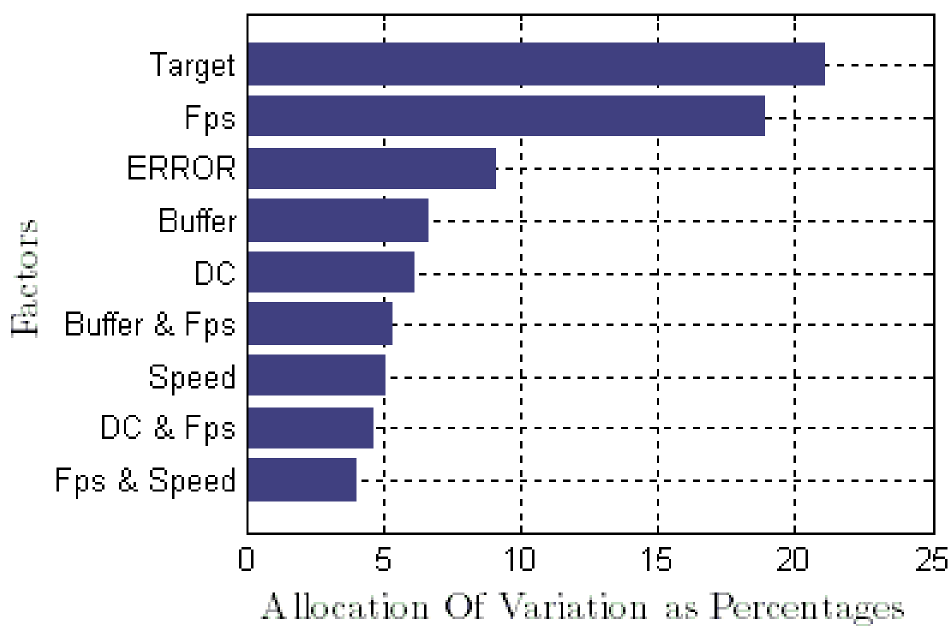


Figure 2.8. Effects of the system parameters on the number frames received at sink

In Figure 2.7 and Figure 2.8, the effects of the number of targets and the frame rate factors are again very significant. Also, the effects of the buffer size and the duty cycle have the same behavior as in the source drop case as shown in Figure 2.2 and Figure 2.3.

2.2.1. Discussion

In the tests described in this section, we observe the effect of some significant variables in a surveillance application. Throughout the tests one can easily conclude that high frame rates and larger number of targets can degrade the network performance significantly. The effects of both parameters are so high that we cannot evaluate the effect of other parameters rigorously. Therefore, separate tests should be done in which the frame rate and the number of targets should be fixed according to application requirements. We can suggest using frame rates between three - four fps.

The effect of the target velocity is mainly observed in the congestion cases. Since when the target velocity is increased, the dwell time decreases which results in short data streams from multiple nodes compared to long data streams from less sources in reduced velocity. Therefore, we observe data loss on the way rather than at the source. When we investigate the effect of the buffer, we observe that increasing the buffer size is not a solution for the data loss since larger buffers contribute to higher latencies. If we use a timing dependent protocol such as TCP in the transport layer, all the late packet will be recognized as lost packets. Lastly, the duty cycle is directly related to the available bandwidth. Higher duty cycle levels increase the application performance. However, it is obvious that there is a trade-off between the bandwidth and the energy of the nodes. The main energy conservation technique on the nodes is duty cycling, therefore, reasonable levels are required for a long network lifetime.

3. EFFECT OF VIDEO FRAME FRAGMENTATION ON THE PERFORMANCE OF VIDEO SENSOR NETWORKS

In this chapter, the effect of Message Passing (MP) fragmentation support of SMAC [22] on the network performance is evaluated and an improved adaptive version of MP, namely Adaptive Message Passing (AMP) is proposed. Results of extensive simulations with realistic parameters indicate that both MP and AMP significantly improve the video quality in VSN.

3.1. Message Passing in SMAC

In a wireless link, the retransmission of the whole frame is very costly in case of an error, therefore fragmenting the frame and sending as several packets is preferred. However, this choice also brings a new overhead on the communication. Before sending each packet, in order to avoid the hidden terminal problem, we employ *Ready to Send / Clear to Send (RTS/CTS)* mechanism which leads to an under-utilized link and longer delays. For instance, four nodes are deployed such that node A_1's transmission is heard by A_2 and A_3, node A_3's transmission is heard by A_1 and A_4. As in Figure 3.1, when A_1 wants to transmit a packet to A_3, it first sends an RTS message then after getting the CTS message A_1 begins transmission. Meanwhile, other nodes A_2 and A_3 go into SLEEP state when they hear the control messages to prevent overhearing.

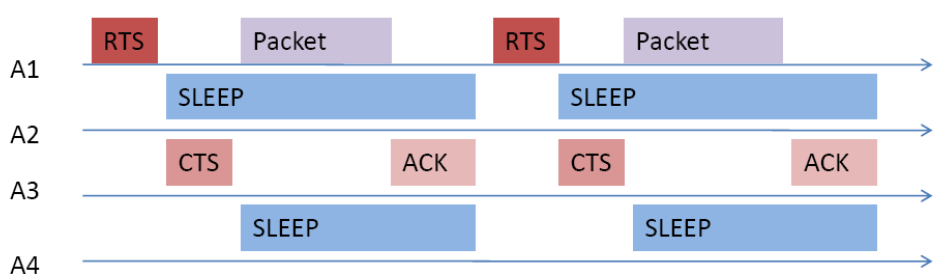


Figure 3.1. Message sequence in SMAC without using Message Passing

In SMAC, a fragmentation method called *Message Passing (MP)* is proposed in order to decrease the use of *RTS/CTS* messages [22]. The frame is fragmented into packets then sent in bursts. As shown in Figure 3.2, RTS/CTS messaging is done only before the first packet. The rest of the packets are sent after getting the ACK message of the previous packet.

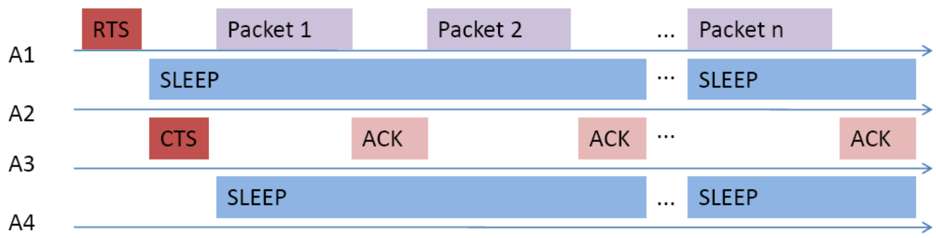


Figure 3.2. Message sequence in SMAC using Message Passing

In MP, all packets including the control packets involve the whole transmission duration of the frame. However, in the *802.11* standard each packet carries only the consequent packet's duration. When an error in the wireless link exists in *802.11*, all nodes contend for the medium and can break the burst. However, with MP in case of an error since the packets carry the whole frame duration, other nodes cannot interfere with the frame transmission. Also, in the case of an error the retransmission time is added to the whole duration. Thus other nodes do not interfere with the burst till the end, even if they wake up during the transmission.

3.2. Adaptive Message Passing

When a node hears an RTS/CTS message which is not destined to it, the node immediately turns off the radio to prevent overhearing, then turns on the radio according to the end of the transmission period and its duty cycle schedule. When a retransmission occur because of an error in the wireless link, since the node is sleeping, it cannot realize the new updated duration. After waking up, the node assumes that the transmission is over and may interfere with the ongoing transmission by sending a packet. In order to avoid this unexpected behavior, the node should listen to the medium and not transmit anything for a data and ACK packet duration. If there is no transmission, it can contend for the medium.

However, in that additional listen period, the nodes which establish the previous communication can contend for the medium for a new one while other nodes are waiting till the end of the period. Thus same nodes can gain control of the medium successively and does not release it as long as they have packets to send.

In order to establish fairness among the nodes, they should wake up at the end of the ongoing transmission while sleeping and listen to the medium. If they do not hear anything, they realize that the transmission is over and they can contend for the medium at the beginning of the scheduled listen period. Thus, in a normal scheduled listen period, the nodes will have equal right to contend for the medium. Because of its adaptive behavior, this newly proposed MP method is called as Adaptive Message Passing (AMP).

3.3. Results

OPNET simulation environment is used to evaluate the effect of MP and AMP under a video surveillance application scenario. SMAC with MP is used at the MAC layer and Greedy Perimeter Stateless Routing (GPSR) [54] is used for routing. GPSR is a geographical routing technique in which we assume that nodes are aware of the location of the their neighbors and the sink location. Simulation parameters are set as summarized in Table 3.1.

As shown in Figure 3.3, MP and Adaptive Message Passing (AMP) perform better than the ordinary SMAC. In lower duty cycle values such as 5-15 per cent, it is hard to talk about a video quality without MP. However, MP and AMP offer reasonable video qualities with high delivery rates. Moreover, especially with five per cent duty cycle, AMP outperforms MP.

On the other hand, why is plain SMAC so poor? In our simulations, length of SYNC, LISTEN and SLEEP periods are set with respect to the size of RTS/CTS messages, contention windows, and for five per cent duty cycle, they are three, six and 190 ms, respectively. Also note that one packet is sent in four ms. When we make a

Table 3.1. Simulation Parameters

Paremeter	**Value**
Surveillance area	$400 \times 400\ m^2$
Network size	100 nodes
Deployment type	Uniform random
Video frame size	10 kbits
Packet size	1 kbits
Camera frame rate	3 fps
Field of view	52 deg.
Camera detection range	30 m
Bandwidth	250 kbps
Buffer size	100 kbits
Target mobility model	Random Waypoint

rough computation, in MP in order to send one frame, we need a SLEEP + SYNC + LISTEN + 10× PACKET DURATION = 239 ms. However in plain SMAC, we need $10 \times \{$SLEEP + SYNC + LISTEN + PACKET DURATION$\} \approx 2 seconds$ which is nearly 10 times larger than the MP case.

In the above scenario, MP has one exception. When a node wants to send a frame immediately after a neighbor node's transmission, it waits for one schedule as explained in Section 3.2. Then it needs $2 \times \{$SLEEP + SYNC + LISTEN$\}$ + 10× PACKET DURATION = 438 ms to transmit the frame, however AMP still needs 239 ms. Therefore, in congested scenarios, AMP offers better video quality.

To further understand the effect of MP on the traffic, we should consider the latency of packets since in time critical applications such as surveillance, timing is highly important. As shown in Figure 3.4, MP and AMP transmit packets in reasonable times and significantly improve the latency. Also, it should be noted that AMP again outperforms MP.

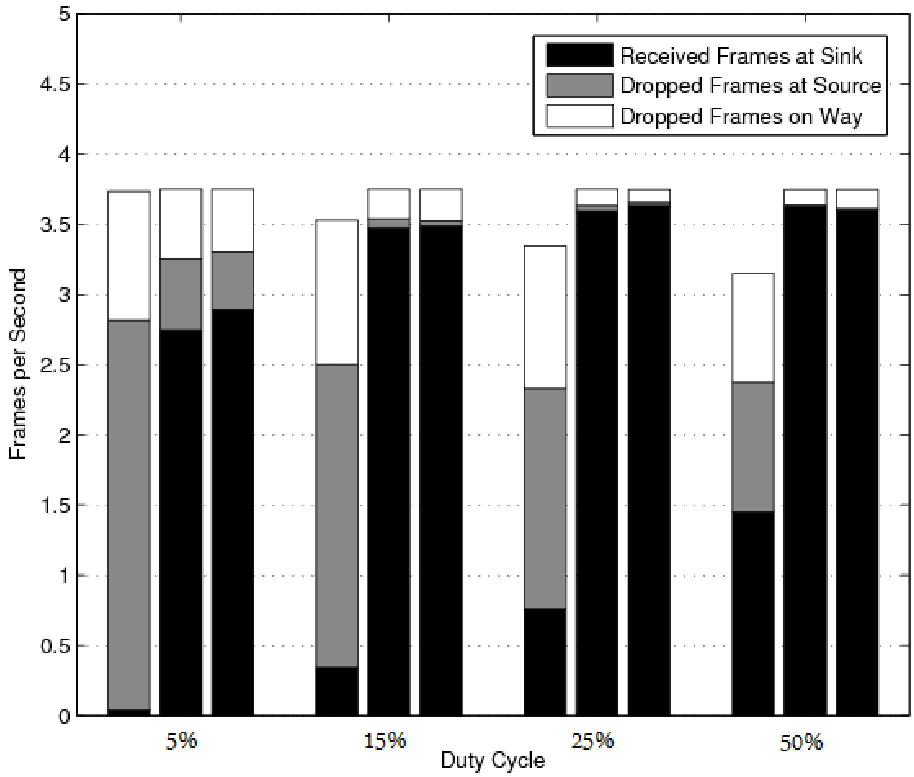


Figure 3.3. Frame delivery with different duty cycle values. (In each block from left to right: Without MP, MP, AMP)

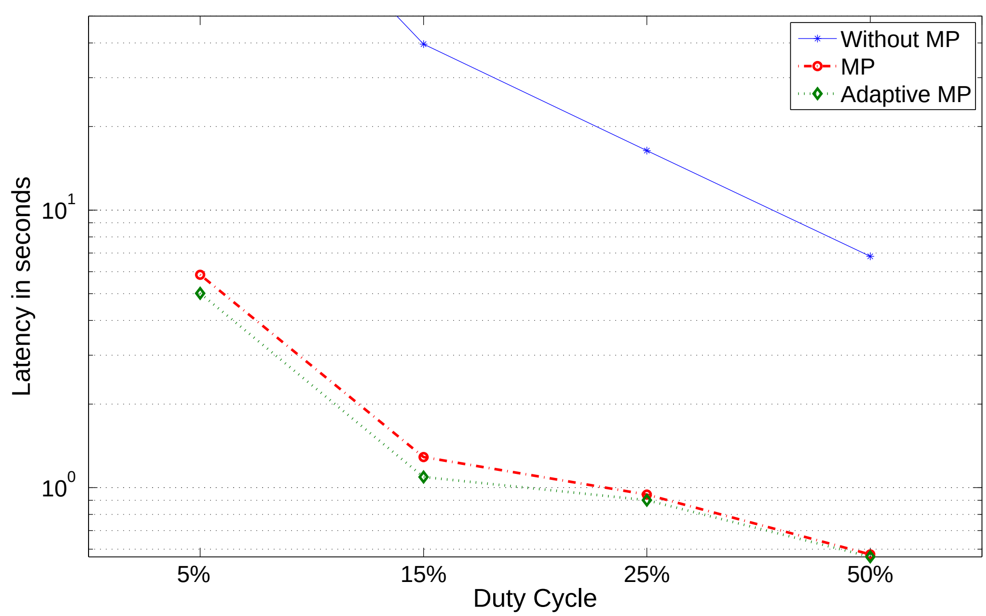


Figure 3.4. Latency of packets under various duty cycle values (in log graph)

One can easily conclude that in streaming applications, rather using plain medium access methods, intelligent fragmentation methods should be preferred. Also with such methods, all the related packets of the application are relayed using the same route which enables us to implement wise scheduling and queueing techniques that increase the application performance as discussed in the next chapter.

4. EVENT BASED FAIRNESS FOR VIDEO SURVEILLANCE SENSOR NETWORKS

In this chapter, the fairness issue among events is investigated. It is argued that the initial frames of an event deserve special care since they contain much of the visual information and also the delay experienced by them directly affects the reporting delay. Therefore, a scheduling mechanism that gives priority to the initial frames is proposed. In this chapter only single path routing algorithms are considered, in Chapter 5 multi-path routing algorithms are also covered.

4.1. Motivation

When we focus on the contents of an event-flow, we observe that there is spatio-temporal redundancy among consecutive frames. This is mainly because the camera module of the sensor node takes continuous snapshots of the scene with a certain frame rate. It is not possible to generically define the number of frames to be received at the sink for healthy reception of the event.

This depends on the type of detection method run on the back end. This could range from simple event detection in which only the existence of the event is notified to the classification or the identification of the target. Also the frames received could be an input to an image recognition engine or to an human operator. Another factor is the specific positioning and movement of the target within the visual sensing range. A target closer to the camera module takes a bigger portion of the picture, however assuming that the target is mobile, proximity to the sensor also implies shorter residence time inside the sensing range, hence a shorter event-flow. Therefore, we can crudely conclude that event-flows, as they become longer, contain more frames of the scene and likely to have more redundancy among frames. The information contribution of the individual frames of a generic event-flow is depicted in Figure 4.1.

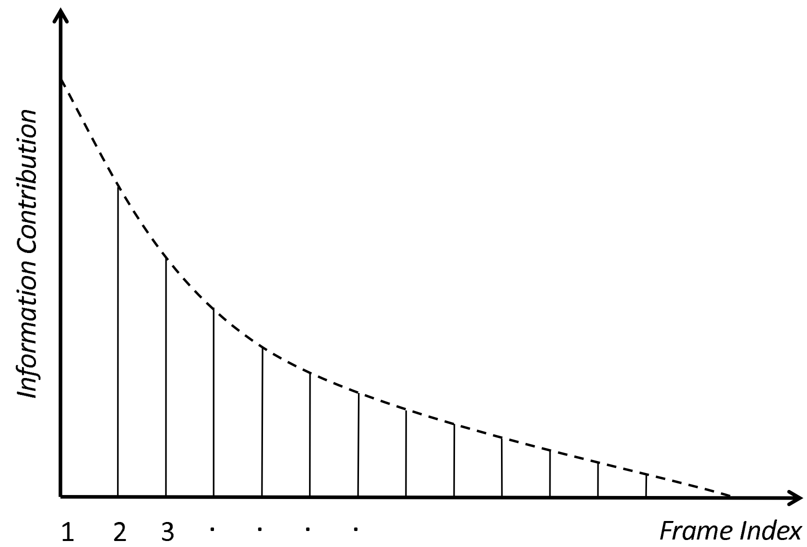


Figure 4.1. Information contribution of individual frames of a surveillance video event-flow.

With this observation in mind, it can be claimed that irrespective of the duration of the events, initial frames of an event deserve special care. That is because they contain the earliest visual information and also the delay experienced by them directly affects the reporting delay. In this work, the initial frames are given priority via an application level fair queue management scheme, namely *Event Based Fairness*.

4.2. Providing Application Level Fairness with EBF

WSNs, including VSSNs, have the unique characteristic that the network is designed to achieve a common specific task, in which all the nodes operate collaboratively. Opposingly, in the previous wired and wireless networking paradigms, we can see the clear distinction between the applications running on the nodes and the communication service provided by the network. In this picture, the nodes care about maximizing their own utility and not necessarily respecting the network wide resource scarcity. Therefore, previous studies on the fairness mainly focused on the per-node and the per-flow based fairness. For a WSN, on the other hand, the individual nodes may not need to obtain fair service at all times. However, fairness becomes a crucial issue when considered in terms of the application performance.

The performance of a VSSN application depends on how well the events are reported, i.e. the video quality of the events conveyed and the initial reporting delay which are related to how events are handled and processed in the network. In the standard FCFS queueing approach, the frames of the events are queued in the nodes according to the their sequence of arrival. A burst event with many frames fills the head of the queue in the relay node and other events can only utilize the space left from the former event. The rest of the events have to wait till the frames of the previous events are served. Moreover, in the case of buffer overflow, only a few of the packets of the forthcoming events can be relayed. As a result, when FCFS is preferred, while some events are reported with high quality and low latency, others are received in low quality and high latencies. In order to guarantee a certain Quality of Service (QoS) in video quality and acceptable reporting latency, an event-aware fair queue management scheme called EBF is proposed that is streamlined for VSSN applications.

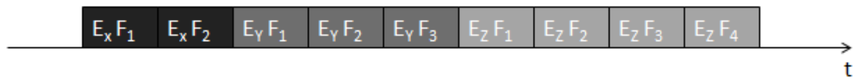
4.2.1. Round Robin Based Implementation of EBF

Round Robin based EBF implementation (EBF-RR) strives to give fair service to all events that are currently enqueued in a VSSN node. The queue is composed of frames received from the network for relaying purposes and the frames received from the application layer, i.e. the video frames produced by the node itself. Also a node can uniquely identify the frames in its queue according to the events they belong to by using the source node id and the local event id assigned by the source node. EBF-RR operates by servicing frames of events in a round robin manner, one frame from each event at a time. Internally, EBF-RR dynamically forms logical queues for each event and gives service to each queue in a time-shared manner. The duration in which all event queues are served once is called an *epoch*. During an epoch, the available bandwidth is equally divided among each event. The overall service rate an event gets from EBF-RR depends on the length of the event (in terms of frames) occupied in the main queue, the total number of events in the queue, the length of each event in the queue and the congestion level experienced at the MAC level (available effective bandwidth). When the incoming frames are more than the capacity of the node, buffer overflow occurs. In that case, EBF-RR drops the frame from the longest event queue. With this scheme a received frame that arrives at the full main buffer need not be dropped unless it belongs to the event that currently has the longest logical queue. When compared with the FCFS behavior, EBF-RR provides fair bandwidth allocation to events and also gives priority to events with fewer frames. This latter property is especially more pronounced in the case of buffer overflows in which frames of events with longer queues are dropped. In that sense, EBF-RR tries to homogenize the service rate among events according to the snapshot of the queue. Visual comparison of EBF-RR and FCFS is depicted in Figure 4.2.

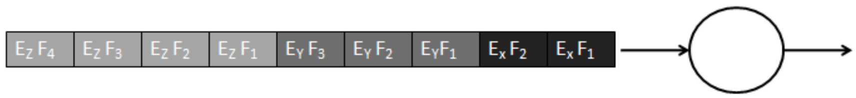
One point to note in the above discussion is that the queue manipulation is done in terms of frames and not packets. Normally, it is straightforward to process a queue in terms of frames since each packet has a packet identifier, however there is no guarantee that a frame will be received completely from the neighbors due to packet drops. Therefore in our VSSN implementation, *SMAC* [22] with *Message Passing* feature is used as the MAC layer. Since Message Passing allows frames to be passed among nodes intact which makes our assumption about frame based queue manipulation possible.

4.2.2. LAS Based Implementation of EBF

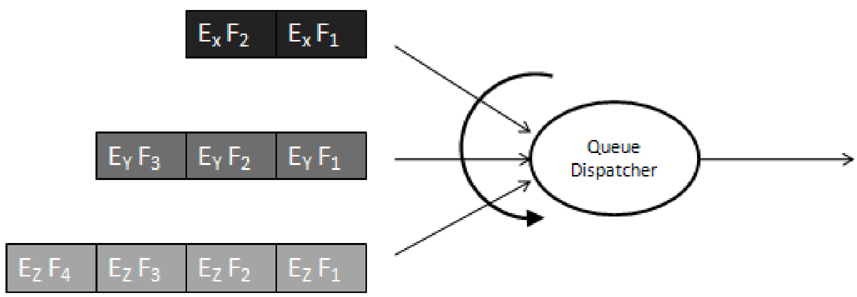
The main idea behind LAS Based EBF (EBF-LAS) is that an event is a sequence of frames flowing in the network and at a specific time instance, only a portion of it may be contained in the buffer of a VSSN node. This is due to the buffer size limitations and earlier frame drops that an event may experience. EBF-RR operates on the instantaneous snapshot of the buffer and provide fairness among events according to what is currently present. In this respect, a way to provide better fairness among events is to consider not only the current buffer composition but also to take into account the frames of an event that has been relayed previously. EBF-LAS, like EBF-RR, forms logical queues of frames per event and service one frame from each queue in an epoch in a round robin fashion. However, unlike the RR implementation, EBF-LAS keeps track of the sent frames and inserts a virtual frame to the event queues as place



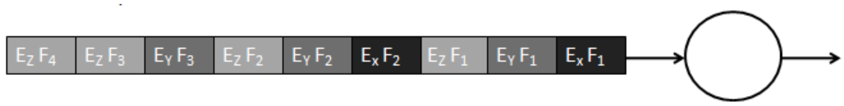
(a) Arriving sequence of the frames of the events (E_iF_j stands for j^{th} frame of i^{th} event)



(b) The resulting queue obtained by FCFS



(c) Logical queues formed by EBF-RR



(d) The resulting queue obtained with EBF-RR

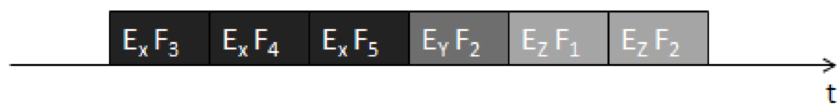
Figure 4.2. The comparison of EBF-RR with FCFS.

holders for each frame of an event that is relayed. Therefore, a logical queue for an event contains both real frames that are waiting to be send and virtual frames that are already sent. In every logical event queue, virtual frames are placed in the front of the queue, therefore, when deciding on the next frame to get relayed, EBF-LAS gives explicit priority to the events that have fewer frames sent. Figure. 4.3 shows a sample sequence of incoming frames and how they are enqueued both by the RR and the LAS EBF implementations.

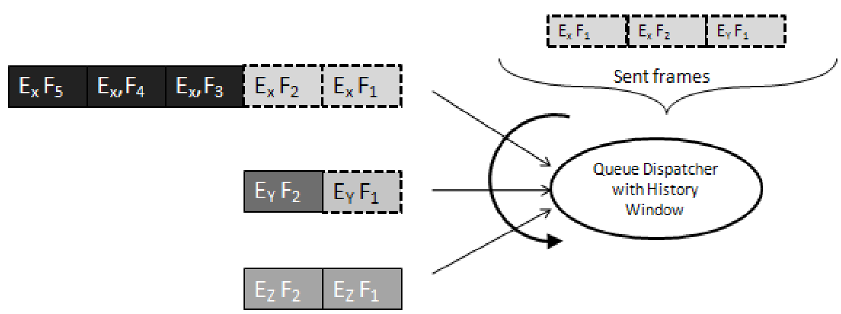
4.3. Comparative evaluation of EBF-RR, EBF-LAS and FCFS

4.3.1. Experimental Setup

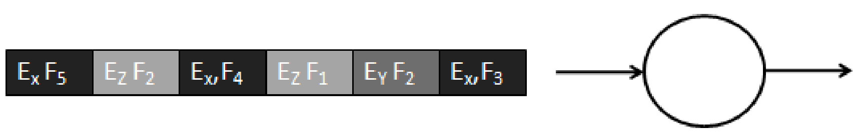
We examine the effect of EBF-RR and EBF-LAS using the OPNET simulation environment [59]. In order to observe the improvements on the reporting latency and the video quality of events in detail, a surveillance scenario is examined. In a geographical area that is under surveillance not every path is equally likely to be used. The paths which intruders have higher tendency to follow are called *Trespassers' Favorite Path* (TFP) [64]. TFPs are preferred over other alternatives due to the reasons such



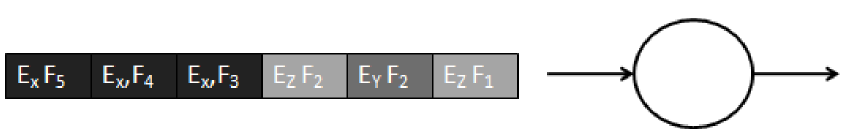
(a) Arriving sequence of the frames of the events (E_iF_j stands for j^{th} frame of i^{th} event)



(b) The history window and logical queues formed by EBF-LAS



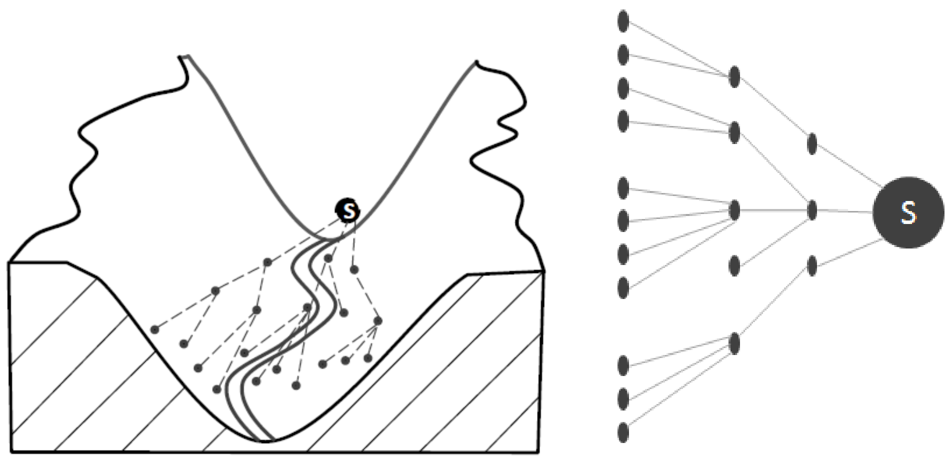
(c) The resulting queue obtained with EBF-RR



(d) The resulting queue obtained with EBF-LAS

Figure 4.3. The comparison of the RR with the LAS implementation.

as easy geographical conditions and remoteness to checkpoint locations. For effective operation, existence of TFPs should be considered when designing a surveillance network, as large portion of the total traffic is likely to be originated from sensor nodes located within the TFPs. In our surveillance scenario, we have simulated the traffic created in a valley-type TFP which contains 19 VSSN nodes, as depicted in Figure 4.3.1.



(a) Trespassers' Favorite Path (TFP)

(b) Detailed view of the TFP multi-hop simulation scenario

Figure 4.4. Deployment Scenario. Intruders follow the favorite path in which the sensors are deployed more densely.

In video surveillance applications, the volume of the data traffic is related to the dwell time of the target, the camera frame rate and the compression algorithm. The duration of an event and the number of frames created during the event varies according to these parameters. In our tests, we model the traffic creation using event size, Ψ, frame interarrival time, Δ_F, and event interarrival time, Δ_E. Ψ denotes the number of frames contained in an event, whereas Δ_F is the frame generation rate of the camera modules of the VSSN nodes. Δ_E models the time between two consecutive events a sensor node detects. Values for Ψ, Δ_F, Δ_E and other related simulation parameters are presented in Table 4.1.

Preliminary experiments are run to fix the buffer capacity that is allocated on the individual nodes. Enlarging the buffer enhances the throughput at the expense of

Table 4.1. Simulation Parameters

Parameter	Value
Event size (Ψ)	Normal distributed with ($\mu = 15$,$\sigma^2 = 7$) frames
Video frame size	10 kbits
Packet size	1 kbits
Frame interarrival time (Δ_F)	Constant with 1/3 sec
Event interarrival time (Δ_E)	Exponentially distributed with $\mu = 25$ sec
Duty cycle	$10\%, 20\%^{*}, 30\%, 40\%$
Bandwidth	250 kbps
Buffer size	100 kbits
MAC layer	SMAC [22] with Message Passing feature
Number of repetitions	20
Confidence interval	95%

(*)Unless otherwise specified, 20% duty cycle is the default in the experiments.

increased delay. After a threshold value, larger buffer sizes result in intolerable delay levels [65]. The chosen buffer size (100 Kbits) is within an operationally feasible region in which the delay-throughput balance is observed. Please refer to [66] for a detailed study in which the effects of the factors like buffer size, camera frame rate and MAC duty cycle on the VSN performance are systematically examined.

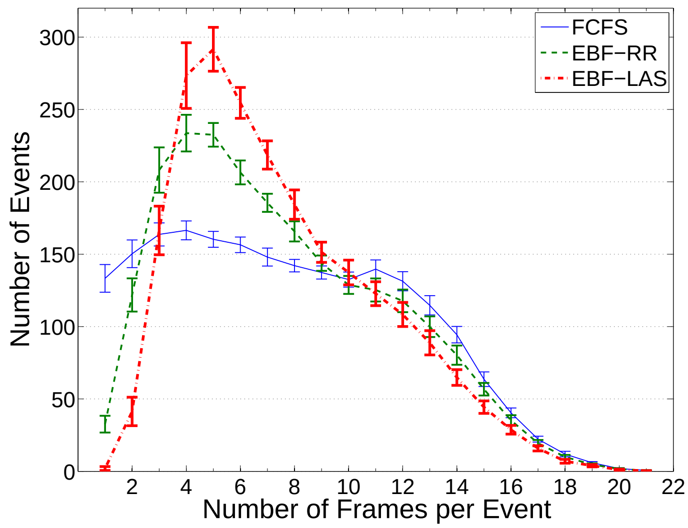
4.3.2. Results

A histogram summarizing the events according to the number of successfully received frames at the sink is presented in Figure 4.5(a). Out of the 2220 events generated, for the FCFS case, for instance, around 130 events are reported only with a single frame whereas around 90 events are reported with 14 frames. The number of events reported for all queueing mechanisms are close to each other 2122, 2215 and 2211 for FCFS, EBF-RR and EBF-LAS respectively. However, it is observed that the variance in the frequency of the frames per event is decreased by EBF-RR and EBF-LAS. In the $1-3$ fps interval and $10-20$ fps interval, the number of events are less in EBF-RR and EBF-LAS cases than FCFS since EBF-LAS and EBF-RR decreases the number of over reported events and share the available excess bandwidth among the under reported events. Thus, most of the events are reported similarly which is due to the fair treatment of frames according to the related events.

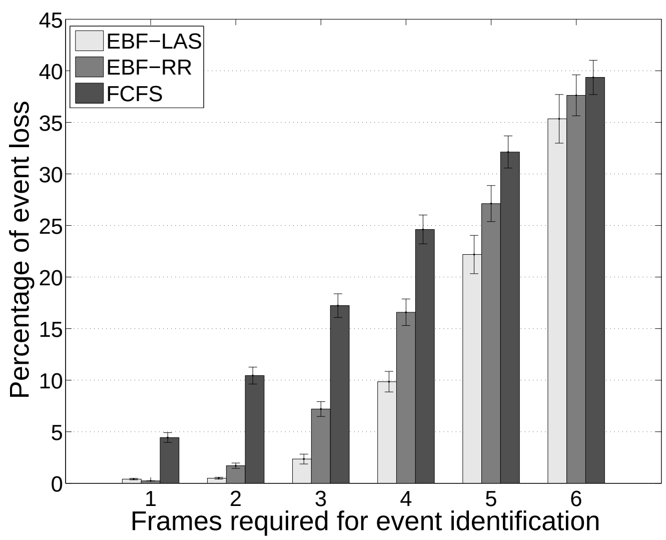
The total number of frames required to be received at the sink in order a triggered event to be considered as "*detected*" depends on the application. However, as previously pointed out, it is the initial frames of an event that contribute more to the visual information received at the sink. In order to observe the effect of EBF-LAS and EBF-RR on the reliable event reporting, we plot the ratio of missed events in Figure 4.5(b). As expected, when the required frames per event is increased, missed event ratio also increases in all queueing techniques. However, the ratio of missed events are clearly less in EBF-RR and EBF-LAS cases compared to that of the FCFS case. For instance, when the required frames for event identification is set to 4, while FCFS misses 24% of the events, EBF-RR misses 17% and EBF-LAS misses less than 10%. Additionally, the difference between the FCFS, EBF-RR and EBF-LAS systems decreases as the number of required frames increases. The reason is that EBF-LAS punishes the large events while giving precedence to smaller ones especially when the network load becomes high.

Besides the video quality, the reporting latency of the events are also important. Especially the frame of an event which arrives first to the sink has the most significant contribution for the event reporting since it makes the sink aware of that event. Figure 4.6(a) presents the average of the first frame latency of the events with various duty cycles and indicates that EBF-RR and EBF-LAS improve the event reporting delay significantly compared to the FCFS case.

To have a more general understanding of the latency behavior of the events, Figure 4.6(b) depicts the average delay a certain frame of an event experiences, e.g., the average latency of the 8^{th} frame of the events. It is observed that EBF-LAS decreases the delay for all frames of the events, whereas EBF-RR performs better than

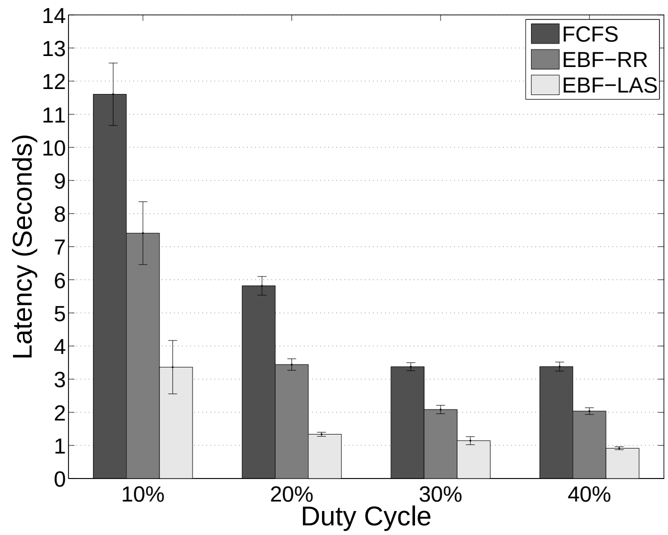


(a) Histogram of number of frames received at sink for each event.

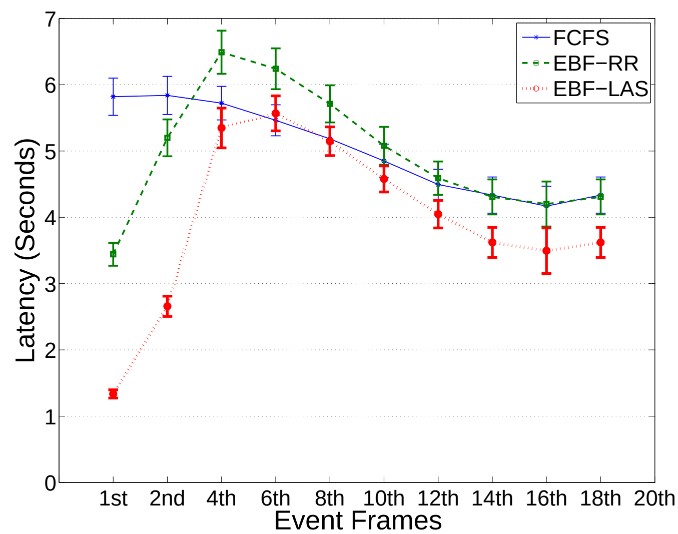


(b) Missed event ratios with different number of frames.

Figure 4.5. Histogram and miss ratio (for identification) for events which are composed of variable number of frames.



(a) Average delay for the first arriving frame of an event.

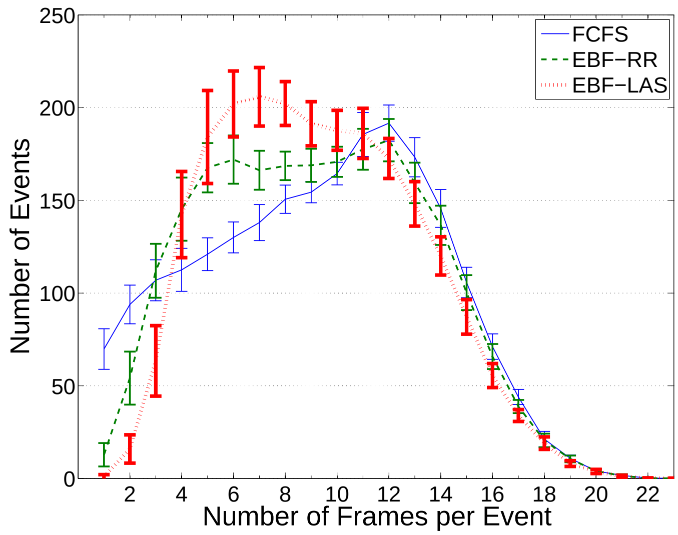


(b) Average latency of frames.

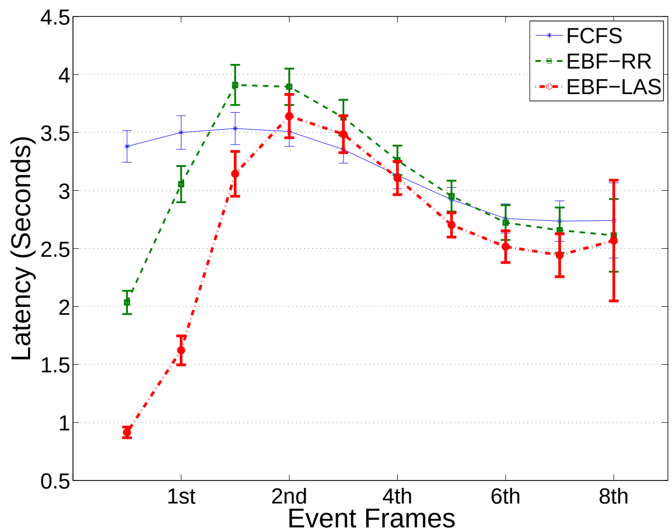
Figure 4.6. Frame latencies of the events.(20 per cent default duty cycle)

FCFS up until the 4^{th} frames of the events. In other words, EBF-LAS decreases the mean response time for all frames of the events.

On the other hand, when the duty cycle is increased, most of the frames arrive to the sink. Therefore as in Figure 4.7(a), the difference between the intelligent queueing techniques and the FCFS decreases. However, as observed in Figure 4.7(b), compared



(a) Histogram of number of frames reached to sink for each event



(b) Average latency of frames

Figure 4.7. Latency and Histogram of the events. (40 per cent duty cycle)

with FCFS, EBF-RR and EBF-LAS can relay all frames without a significant sacrifice in terms of latency.

5. FURTHER IMPROVEMENTS IN EVENT BASED FAIRNESS

In the previous chapter, EBF is introduced for single path routing schemes in multi-hop sensor environments. In this chapter, EBF-LAS scheduling system is employed in multi-path routing algorithms and the contention window size is adjusted in order to improve the latency and arrival rate of the initial frames of events.

5.1. Discussion on the Multi-path Routing Algorithms

In sensor networks, multi-path routing algorithms are implemented in order to increase the reliability or the bandwidth for the application. If the application requires reliability, than each packet is duplicated and transmitted through different paths independently. Thus even if one of the paths are terminated by a node failure or medium noise, the duplicate packets relayed from the other path can reach to the sink. Although in this scheme the network resources may seem to be wasted, if the reliability is the key metric for the application, we should add these redundant paths.

Additionally, multiple paths from source to destination can be incorporated to increase the bandwidth available to the application. Instead of utilizing the bandwidth obtained on a single path, by transmitting the packets from independent paths, we can send the data in a parallel way to the sink. Thus the bandwidth utilized by the application is improved. In VSNs, since the applications demand high bandwidth values, by adding more paths to the sink is a solution for improving the the number of frames received at the sink which means improving the video quality.

5.1.1. Distributed EBF-LAS Implementation on Multi-path Routing Schemes

Since multi-path routing algorithms are expected to be employed in VSNs, we need to modify our EBF-LAS scheduling scheme which is designed for single path routing. In Chapter 4, we have described the EBF-LAS implementation which is based on storing the history of the event's frames which are relayed from that particular node. When the routing scheme allows only single paths each frame follows the same route and the nodes can set the priority of the frames according to the history of the events. However, in multi-path schemes, the frames of the events are relayed from different paths therefore, the history of the events in the individual nodes does not denote the state of the whole network.

In order to overcome the problem described above, a unique sequence number is assigned to each frame of the event and in the queue smallest sequence numbers are assigned higher priorities. The frames of different events with the same sequence numbers are served in the first come first served order.

In the case of frame losses on the network, the numbering scheme given above cannot be able to denote the exact amount of service given to each frame. However, it is a simple method that does not waste the network resources such as additional control packets or memory.

5.2. Variable Contention Window for Increased Fairness

When we deploy distributed EBF-LAS scheduling on the nodes, we achieve fairness among the events. The frames of the events are ordered in the queue according to the provided service to the event they belong to. By ordering the frames, we specify which events should get the precedence in order to capture the medium. Although the events are served in each node based on EBF-LAS, when the nodes try to capture the medium in order to relay the frames, each event has equal chance. In CSMA based systems, since the contented slot is mostly chosen by a uniform distribution, there is no prioritization among the flows from each node. Therefore, the fairness among the events from different nodes could not be achieved.

In order to achieve fairness between the flows of different events, variable contention window sizes can be applied to each event. According to the priority of the event, we can adjust the size of the contention window and give explicit priority to the events which has served less.

In order to observe the effect of variable contention sizes on the fairness of the events, we apply a simple mechanism which divides the contention window into three differentiated equal sized partitions. The first partition is dedicated to the frames of events with sequence numbers one, two and three, the second partition is dedicated to fourth, fifth and the sixth frames of the events, lastly the rest of the frames reside in the third partition.

5.3. Experiment Setup

We examine the effect of EBF-LAS using the OPNET simulation environment [59] in a surveillance application. As stated in Chapter 4, due to geographical conditions and remoteness to checkpoint locations, intruders tend to follow some favorite paths (TFP) in the surveillance area. The network traffic is dominated by these favorite paths. In the simulation scenario, in order to represent the traffic characteristic of such a favorite path, intruders are moved in random waypoint mobility model in a narrow path as shown in Figure 5.1. A new event is created when a camera detects activity and the frames which are labeled with the event id, are created according to the camera frame rate. In the experiments, we compare the performance of FCFS, EBF-LAS and EBF-LAS with Differentiated Contention (EBF-LAS-DC) feature. The simulation parameters are depicted in Table 5.1.

5.4. Results

A histogram summarizing the events according to the number of successfully received frames at the sink is presented in Figure 5.2(a). For instance, for the FCFS case, around 70 events are reported only with a single frame whereas around 120 events are reported with 9 frames. Histogram graph shows us, by enabling EBF-LAS scheduling, we can improve the video quality and fairness for the events. While most of the events are reported with few frames in FCFS scheduling, in EBF-LAS and

Table 5.1. Simulation Parameters

Parameter	**Value**
Surveillance area	$400 \times 400\ m^2$
Favorite path	$10 \times 400\ m^2$
Number of sensors	200
Camera field of view	30 meters with 52 degrees
Sensor node deployment	Uniform deployment
Video frame size	10 kbits
Packet size	1 kbit
Camera frame rate	Constant with 0.25 sec
Number of targets	10
Target velocity	3 m/s
Duty cycle	15%
Bandwidth	250 kbps
Buffer size	100 kbits
MAC layer	SMAC [22] with Message Passing feature
Routing layer	DGR [53] with three paths

EBF-LAS-DC, we observe that the number of events which are reported with higher number of frames increases. Although intelligent scheduling schemes seem to increase the number of frames received at the sink, in fact they are decreasing the number of over reported events, and share the available bandwidth among the less reported events. In order to depict this behavior, we plot a traffic contribution graph at the sink as in Figure 5.2(b). The contribution graph is again a histogram, however this time each bin is multiplied with its x value. For instance, the traffic contribution of events which has reported with 9 frames is 850, 1200 and 1500 frames for FCFS, EBF-LAS and EBF-LAS-DC respectively. In the contribution graph, it is more obvious that intelligent queueing methods decreases the number of both the less reported and the over reported events while increasing the medium reported events.

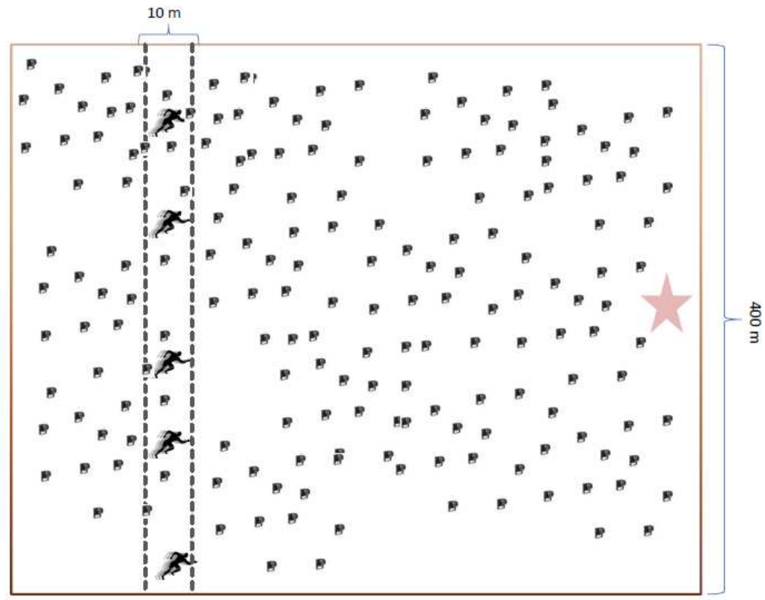
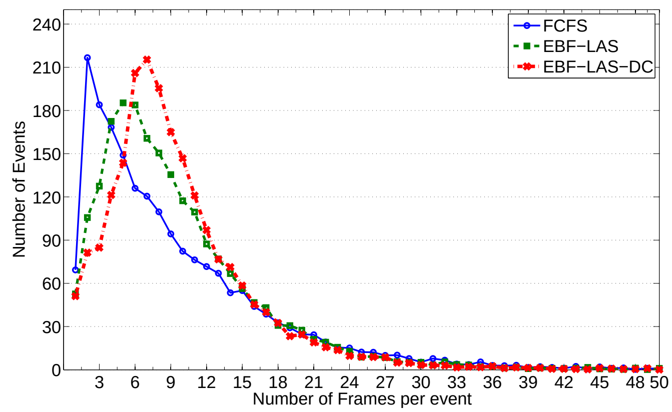
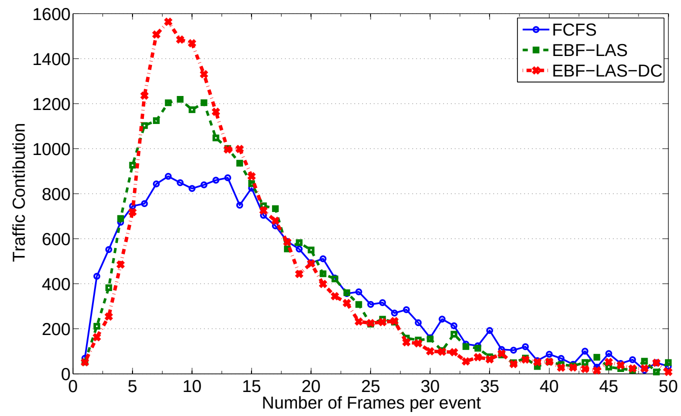


Figure 5.1. Surveillance area with favorite path

As stated previously, we have two goals to employ such scheduling schemes. One is offering a more fair network which is observed in the graphs given in Figure 5.2, the other goal is reducing the event reporting latency. As in Chapter 4, we again define the event reporting time as the time of the first arriving frame since the arrival of the first frame indicates the existence of an event. In Figure 5.3, the latencies of the frames of the events are depicted. The latencies of the initial frames are shown to be reduced with EBF-LAS and EBF-LAS-DC and also it is observed that EBF-LAS has better results with respect to FCFS for all the frames shown in the figure. However, in the EBF-LAS-DC scheduling, while the initial frames have lower latencies, the latency of the frames that have less priority encounter higher delays which results in higher jitter values for the videos. The reason of high jitter is that the back of the contention window is reserved for frames with higher sequence numbers. Hence, there is a tradeoff between the initial reporting delay and the jitter. The priority mechanism implemented in the form of variable contention windows can be fine tuned according to the requirements of the application.



(a) Histogram of number of frames reached to sink for each event



(b) Traffic contribution of events

Figure 5.2. Event size histogram and its traffic contribution graph

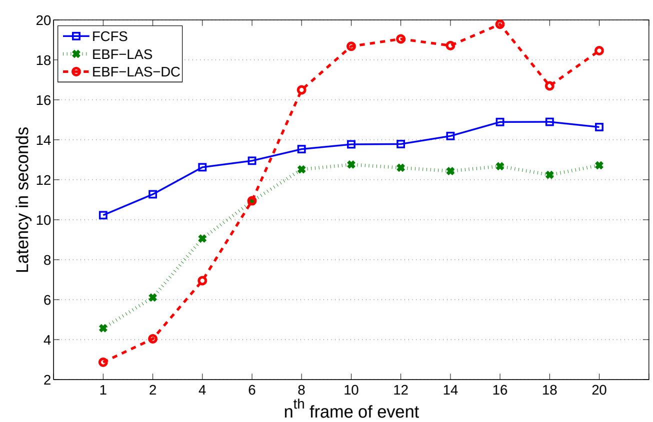


Figure 5.3. Latencies of the frames of the events

6. CONCLUSIONS

In this thesis, we explore the capabilities of the video sensor networks and propose new methodologies in order to improve the application performance. Firstly, a detailed performance analysis is held on VSSNs. The sensor network hardware available in the market formed a realistic application scenario which is evaluated in simulations with a detailed experimental analysis method $2^k r$ factorial design. This method enables us to observe the effect of each parameter not only individually but also in combinations with other parameters. Five significant parameters in VSSNs which are velocity of the targets, number of the targets, duty cycle of the nodes, available memory size and camera frame rate, are involved in the experiments. In order to observe performance key metrics in VSSNs such as latency, packet drop rates stem from congestion and limited memory are chosen.

The performance tests indicate that the high bandwidth requirements of the video traffic cannot be satisfied with traditional sensor network architectures and protocols. The maximum camera frame rates that can be handled by the network is nearly three fps as opposed to 24 fps in normal videos. The received packet ratios are too low for successful event identification in the application layer. When we increase the memory capacity on the nodes in order to increase the packet delivery ratio, the delay incurred by the packets are also increased. These high latency values degrade the application performance since the events are identified in the decision center when the event no longer exists in that particular region of the surveillance area.

Due to the poor performance of the existing architectures, protocols designed for data streaming traffic are added to the application. The preferred MAC is a CSMA/CA based protocol and contains a huge control overhead in the medium access period since before sending each data packet, RTS/CTS messaging is employed. However, frames are the logical unit of the videos not the packets which built the frames. Therefore, an intelligent fragmentation method (Message Passing) which decreases the control overhead by applying the RTS/CTS messaging only before the frame is incorporated with the existing architecture.

In the simulations, we observed that the fragmentation support in the video streaming improve the application performance in terms of latency and delivery ratios. However, MP method has some performance problems in the end of frame transmissions. We discovered the problem and proposed an adaptive version of the protocol and observed an improvement in the metrics.

Although, the application performance significantly improves with fragmentation support, we still encounter packet drops, congestion and latency among the events. Additionally, we realized that the application performance vary among the events created. While some of the events are reported with many frames on time, others are reported with few frames or encounter higher latencies. Therefore, we designed a fair queueing algorithm (EBF) which shares the bandwidth among the events.

Shortest Remaining Processing Time (SRPT) is defined as optimal with respect to the mean response time in systems with Heavy-Tailed service distributions [48]. However, SRPT needs the size information of the flows. Since no prior information about the size of the events is available in VSNs, we implemented LAS scheduling which is defined as "poor man's SRPT: without knowledge of remaining sizes, it does its best to give some priority to small jobs" [48]. We cannot declare intuitively that the event size distribution has high variance in surveillance applications since the distribution is highly correlated with the target object behavior. However, since the aim is reporting the events as quickly as possible and sharing the bandwidth among them, LAS is a suitable scheduling in order to achieve fairness.

Beside the detailed LAS analysis on single path routing, we also presented its behavior on multi-path routing algorithms. In both schemes, we observed reduced latencies and increased fairness in terms of transmitted frames. Lastly, in order to prioritize the events between the neighbor nodes, we applied variable contention window sizes according to service given to the events. The results showed that variable contention size decreases the latency of the initial frames of the events while increasing the latency of the subsequent frames. In other words, modifying the contention window increases the jitter, however it also decreases the reporting delay.

In the future, video sensor networks will be widely deployed due to their promising features. However, there is still a need for new hardware with increased bandwidth and also new cross-layer protocols that relay the frames with pre-processing that classifies the events. As a future work, we can find out how to make in network decisions to prioritize the events. With such a method, more important events can be reported with more frames in less time. Additionally, in order to increase the reliability for selected events, we can employ reactive methods such as ESRT [41]. For example, with an intelligent queueing mechanism, we report the existence of an event quickly, then the decision maker can have time to inform all the nodes in order to increase or decrease the priority of the frames of the event.

Another challenging issue is adjusting the contention windows according to the application requirements. In our work, the partitions are not determined by an analytical method, rather the sizes are arranged intuitively. In order to find out the solution for this adjustment problem, we need to identify the application and network behavior so that we can improve the reporting delay without significantly increasing the jitter.

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