# High Utility Guarantee Video Surveillance System Using IEEE 802.16 WiMAX Networks

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***Abstract*—In video surveillance systems, one of the key design requirements is that video throughput must not fall below a certain limit as the contents must be adequately perceivable. In this paper, we address the problem of guaranteed transportation of critical video flows in wireless WiMAX mesh networks. Our solution is based on the insight that in seeking to construct optimal routing trees and to maximize the network throughput, the problem of assigning the highest possible data rate to source nodes and that of finding the best and efficient forwarding trees from sources to collection points are not independent, the solution of each has a profound impact on the outcome of the other. Therefore, the two problems should ideally be solved jointly. Both problems are essential for the global system performances, in particular in situations of scarce network resources. In this paper, we formulate the global system optimization as an Integer Linear Program (ILP) that maximizes the network utility while satisfying QoS requirements. We also propose a scalable and yet efficient heuristic Joint Routing and Rate Assignment solution, termed JRRA.**

***Index Terms*—WiMAX, Wireless Mesh Network, Utility Maximization, Routing, Rate Assignment.**

## I. Introduction

In this work, we consider a WiMAX system architecture illustrated in Fig. 1, where real-time video feeds collected at various places need to be transmitted to Collection Points (CPs), which are connected to a fixed network. CPs then forward the video data through to one or more video control center(s). Such an architecture can have several practical applications, in particular video surveillance in areas where fixed infrastructures (e.g., optical fibers) are not considered a practical or economically viable solution. WiMAX has been chosen for this system, with its long range coverage, high end-to-end data throughput and more important for its efficient support for traffic management. The quality of service (QoS) of video flows (i.e., throughput, delay and jitter) must actually be controlled in order to be perceivable to the security experts [1]. In WiMAX environment, we can benefit from the provided traffic control mechanisms, but we still need ensure that the system can accommodate as many video flows as possible with the given QoS constraints. In this work, we do not introduce any specific scheduling mechanism such as the one presented in [2], we instead assume legacy traffic management schemes implemented in network cards.

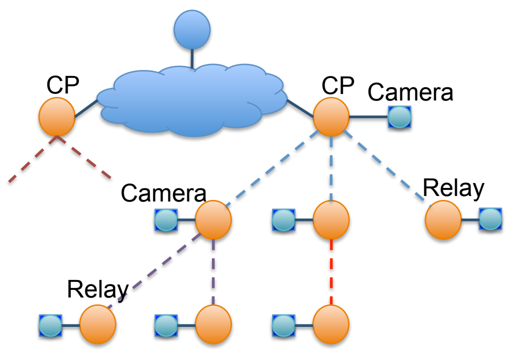


Figure 1. The WiMAX network architecture.

As it is may not be possible for all cameras to directly reach a CP, multi-hop communications are required to forward traffic to the CPs. As current network cards do not currently support multi-hop communications, relays are equipped with two WiMAX cards, one configured as a Base Station and the other as a Subscriber Station. Therefore, a spanning tree(s) rooted at each CP can be built for traffic forwarding, where traffic is aggregated and forwarded by intermediate relays. Each relay is actively associated to only one tree at a given time, but may attach itself to one of the other trees, towards another CP, for failure recovery [3]. We also assume that multiple frequencies are available such that interfering wireless links operate on different channels, enabling multiple parallel transmissions. In order to achieve this, a specific frequency allocation scheme must be implemented in place. Frequency allocation is beyond the scope of this paper, however, it is important to say that this subject has been extensively studied in the literature, in particular in the WIFI environment [4]. In some situations, it may not be possible to transport all flows simultaneously (by construction or due to node failure), so the video operators can assign priorities to the different video flows (e.g., based on their strategic location or because of

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particular events). The system should then be able to favor the critical flows as they represent higher utility for the system

This paper addresses the problem of guaranteed transmission of video flows in the context of this WiMAX mesh network with focus on bandwidth constraints. The problem consists of: (i) Building efficient routing trees, and (ii) Selecting the best data rate of each flow in order to maximize network utilization (i.e., accepting as many video flows as possible (in particular "critical" flows) without violating QoS constraints).

In what follows, we use the terms camera, node and relay interchangeably. The rest of the paper is organized as follows. In Section II, we provide related works, which states the difference between our work and existing solutions. In Section III, we present a formulation of the optimal solution using an ILP. Section IV presents the JRRA scheme, which is then evaluated in Section V. Section VI concludes the paper and briefly introduces our future work.

## II. Related Work

To achieve efficient spectral utilization and high network throughput in WiMAX networks, the route construction within the network is a crucial task. In particular, routing metrics applied in the routing protocol are very crucial. Routing metric, as shown in [5], is generally designed to capture factors that affect the network performance. Many existing routing protocols use minimum hop-count as a performance metric to select the routing path in wireless multi-hop networks [6]. Using the hop-count metric enables rapid convergence, as the minimum hop-count from a node to the core node is determined by physical topology and is thus mostly static. However, simply constructing a routing tree by shortest path is not sufficient to maximize network throughput as the link on the shortest path between two nodes may have bad quality [7], [8], [9]. This is because the shortest path contains the fewest number of hops between the source and destination: Fewer hops may correspond to longer links in order to cover the same distance, which incurs low quality links, and thus operates at low rates [10].

Several routing metrics for finding routes with high end-to-end throughput in multi-hop wireless networks have been proposed recently. Couto et al. [11] presented ETX (expected transmission count), a new metric to find high-throughput paths on multi-hop wireless networks (802.11b), which minimizes the expected total number of packet transmissions (including retransmissions) required to successfully deliver a packet to its ultimate destination. Contrary to the hop-count metric, ETX incorporates link loss ratios, asymmetry in loss ratios between the two directions, and interference among successive links. However, ETX does not perform well for large packet sizes. Draves et al. presented another routing metric in [12], called weighted cumulative expected transmission time (WCETT). The WCETT metric takes into account both link quality metric and the minimum hop-count, and achieves good tradeoff between delay and throughput. The authors assume that all radios on each node are tuned to non-interfering channels with the assignment changing infrequently.

Moreover, various related efforts have explored WiMAX in the context of video streaming applications. Geetha *et al.* [13] proposed a dynamic bandwidth allocation mechanism to achieve fair and efficient allocation. They presented a Generalized Stochastic Petri Net (GSPN) approach to model bandwidth allocation in Broadband Wireless Access (BWA) networks with multiple traffic classes. A dynamic weight assignment mechanism is proposed to enable fair bandwidth allocation among the competing traffic classes. Performance of the weight assignment mechanism is analytically evaluated using the GSPN model. Another research effort was conducted in [14], the authors presented WiMAX fundamentals as a broadband access solution to support IPTV services framework. The authors discussed the considerations associated with delivery video services while minimizing video and audio quality degradation. Furthermore, they presented some key transceiver design considerations at the PHY layer. There has also been effort exploring the performance of scalable video streaming over mobile WiMAX stations using feedback control. In [15], the authors evaluated MAC layer performance by scaling video content over multiple connections based on feedback of the available transmission bandwidth. The authors in [1] proposed a model to improve the utility gain of a live video streaming from cameras mounted on a public transport moving at high vehicular speeds. However, the authors did not consider the different priorities of the cameras, and all cameras are assumed to have the same level of importance.

## III. Optimal Solution

In this section, we present our optimal solution for the joint routing tree construction and rate assignment problem.

### A. Notations and Definitions

For the sake of simplicity, we consider a static topology (no mobility) and ideal radio channel conditions. Our aim is actually to concentrate on the tree structures and rate assignment that are needed in various network topologies and video priorities. We also concentrate on the main QoS parameter, i.e. bandwidth constraints. The proposed WiMAX network is modeled as undirected graph $G = (V, E)$, where $V$ is the set of vertices representing the nodes in the network, and is composed of a group of relay nodes, denoted as $V_N$, and a group of collection points, denoted as $V_{CP}$. $E$ denotes the set of edges that represents the potential communication network topology, i.e. edge $(v_i, v_j) \in E$ iff $v_i, v_j$ are within each other's communication range. Hence, the relays form a multi-hop ad-hoc network among themselves to relay traffic to the CP(s). Each edge $(v_i, v_j)$ has a physical capacity $L_{ij}$, which represents the maximum amount of traffic that can pass through this particular link. We also introduce a simple cell capacity limitation $C_i$ to each node $i$. For sake of simplicity, we assume that each relay node $v \in V_N$ is equipped with a single camera. However, the presented model can be generalized to take into account an arbitrary number of cameras in a straightforward manner.

The neighborhood of a node $v$, denoted by $N(v)$, is the set of nodes residing within its transmission range. Thus, a bidirectional wireless link exists between $v$ and every node $u \in N(v) - \{v\}$, which is represented as an edge$(u, v) \in E$. The number of neighbors of a vertex $v$ is called the degree of $v$, denoted by $\delta(v)$. Once the routing algorithm has been applied, the resulting tree(s) $T = (V', E')$ is a subgraph of $G$, where $E'$ represents the communication links in the final tree(s), and $V'$ is the set of relays and CPs included in the resulting routing tree.

In order to assess the relative importance of cameras and the benefits gained when accepted in the network, we propose a *utility* function as in our previous work [16]. The utility of a streaming video coming from camera $v_i$ is denoted by $U_i$. This utility depends on the minimum acceptable video rate $W_{min}$ and the maximal desired data rate $W_{max}$. It also depends on $P_i$, which identifies the priority associated with each camera (e.g., either high or low). This value can be pre-assigned based on the geographic location of the cameras and the importance of the captured data, and can be dynamically changed by an operator (e.g., via SNMP in case of specific events). We use a simple step-wise linear function for this utility function. Let $r_i$ be the current data rate allocated to camera $v_i$, then $U_i = 0$ whenever $r_i < W_{min}$ as the flow cannot be properly interpreted at the control center. In other words, the video streaming is useless and should be stopped to conserve system resources. Note that, video data can be stored locally, if possible, and will be retrieved later when the bandwidth permit. When $r_i = W_{min}$, the utility reaches a value $P_i U_{min}$ and then smoothly increases with $r_i$ towards $P_i U_{max}$ for $r_i = W_{max}$ (by construction, we must have $r_i \leq W_{max}$).

### *B. Integer Linear Program Formulation*

Let $x_{ij}$ be a 0-1 integer variable for each $(v_i, v_j) \in E$ such that $x_{ij} = 1$ if the edge $(v_i, v_j)$ is included in $E'$ (i.e., the final routing tree). Also, let $z_i$ be a 0-1 integer variable for each camera $v_i \in V_S$, such that $z_i = 1$ if the camera $v_i$ is accepted as a traffic source in the resulting tree (i.e., $v_i \in V'_N$). Let $r_i$ be a positive real variable for each $v_i \in V_N$, representing the effective data rate of $v_i$, such that $r_i = 0$ if $v_i$ is not included in the resulting routing tree (i.e., $z_i = 0$). Our optimization problem is thus to find the tree structure (represented by the variables $\{x_{ij}\}$) and the video rate assignment (represented by $z_i$ and $r_i$). We have also to introduce an additional positive $y_{ij}$ representing the amount of data transmitted from node $v_i$ to node $v_j$ (i.e., uplink effective data rate), where the receiver could be a CP node. The ILP for the routing tree construction and rate assignment problem can thus be stated as follows:

**Objective function:**

$$max \sum_{i \in V_S} z \cdot P_i \cdot U_{min} + z_i \cdot P_i \cdot (r_i - R_{min}) \cdot U_{step}$$

The first term of the utility function is the minimum utility for each camera in the network, and the second term denotes the utility evolution with rate. Multiplying the second term by $U_{step}$ (which is equal to $(U_{max} - U_{min})/(W_{max} - W_{min})$ in this scenario) ensures utility evolution with rate. Also, multiplying the first and second terms by $z_i$ guarantees to consider only the accepted cameras. Note that, each accepted camera $v_i \in V'_N$ is assigned rate $r_i \geqslant R_{min}$ from constraint 8 below.

**Constraints:**

$$x_{ij} \leqslant y_{ij} \leqslant L_{ij} \cdot x_{ij}, \forall i \in V_N, \forall j \in V : (i,j) \in E \quad (1)$$

$$\sum_{\forall j \in V_N : (j,i) \in E} y_{ji} \leqslant C_i, \forall i \in V \quad (2)$$

$$\sum_{\forall j \in V : (i,j) \in E} y_{ij} - \sum_{\forall j \in V : (j,i) \in E} y_{ji} = r_i \cdot W_{max}, \forall i \in V_N \quad (3)$$

$$\sum_{\forall j \in V : (i,j) \in E} x_{ij} \leqslant 1, \forall i \in V_N \quad (4)$$

$$\sum_{\forall j \in V : (i,j) \in E} x_{ij} = 0, \forall i \in V_{CP} \quad (5)$$

$$\sum_{\forall j \in V : (i,j) \in E} y_{ij} = 0, \forall i \in V_{CP} \quad (6)$$

$$z_i \geqslant r_i, \forall i \in V_N \quad (7)$$

$$r_i \geqslant R_{min} \cdot z_i, \forall i \in V_N \quad (8)$$

Inequality (1) ensures that the uplink effective rate of each included edge in the resulting tree is bounded by the maximum physical link capacity. Constraint (2) provides an upper bound (i.e., the cell capacity) on the relay load constraint, it ensures that the incoming flow is always less than cell capacity $C_i$. Constraint (3) is for flow conservation. It implies that the difference between the outgoing traffic and the incoming traffic at camera $v_i$ is the volume of traffic generated by camera $v_i$ itself. Constraints (4) ensures that each camera has exactly one parent. Constraint (5) prevents a CP from having a parent. Constraint (6) denotes that a CP has no uplink traffic within the network. Constraint (7) ensures that camera data rate is assigned to accepted cameras only, i.e., a rejected camera has rate equal to zero. Finally, constraint (8) ensures that each accepted camera $v_i$ in the resulting tree has to be assigned rate $r_i \geqslant R_{min}$, this is to satisfy the minimum acceptable data rate (QoS) requirements..

## IV. Algorithmic Solution

Since the optimal solution of routing and rate assignment problem defined above is hard to achieve for large-scale network instances, we propose a near optimal Joint Routing and Rate Assignment algorithmic solution, termed JRRA, to solve our problem. In this section, we describe the design and implementation issues of the proposed scheme in depth. Our proposed solution consists of two phases described as follows:

**Algorithm 1** Capacity aware routing

**Input:** $prnt(i)$, the current parent of the node $i$. $prnt(i) = \phi$ if the node is joining the mesh. $UplinkCap(i)$, the current uplink capacity. $UplinkCap(i) = 0$ if the node is joining the mesh.

```
procedure PARENTSELECTION(prnt(i),UplinkCap(i))
    for all j ∈ CN do
        Child(j) ← Child(j) ∪ i {add i to j's list of children }
        α_j ← UplinkCap(j)/ |Child(j) |
        if α_j > UplinkCap(i) then
            prnt(i) ← j
            UplinkCap(i) ← α_j
        else
        Child(j) ← Child(j) − i {remove i from j's list of children }
        end if
    end for
    send(j, JOIN-MSG)
return prnt(i)
end procedure
```

### A. Routing

We present a fully distributed capacity-aware routing algorithm that aims at maximizing throughput capacity while establishing the routes. The objective is to select the route with highest end-to-end residual capacity between the joining node and a CP. An illustration of the algorithm is given in Alg. 1.

*1) Choice of routing metric:* Our objective is to select branches with the largest available capacity (end-to-end from a node to one of the collection points) in order to accept as many flows as possible. However, forwarding too much traffic on few branches (with largest capacity) yields to traffic congestion, therefore, we should ensure a good load balancing among the branches. We should also abandon too long routing paths to limit delay and jitter but also in terms of global throughput: the same flow consumes more bandwidth on a long branch, as it reserves resources on more links. Our proposed metric, aims at achieving good tradeoff between all these objectives.

A node connected to a CP periodically broadcasts messages describing the characteristics of the branch (end-to-end). For relay $v_j$, the message sent contains the available bandwidth towards a CP, denoted by $UplinkCap(j)$, and the number of children, denoted by $Child(j)$, that depends on this node. The variables are used to compute a variable $\alpha_{ij}$ (for each node $v_i$ and candidate parent $v_j$) as $\alpha_{ij} = \frac{UplinkCap(j)}{|Child(j)|}$. The selected parent will be the one that maximizes this value: $prnt(i) = argmax\{\alpha_{ij}\}$. This value represents the residual bandwidth considering a fair share between the different branches in the tree. The division between the number of children will lead to balance the flows on different branches and trees towards the different CPs. It is also interesting to note that the $\alpha$ values decreases with the number of hops (the number of children being generally greater or equal to 1), so that longer paths are only used when they bring significant gain in terms of bandwidth. The computation of this value depends solely on the network topology and not the flows to be transported (e.g., the priority of the flows) for sake of stability.

*2) Tree construction:* The tree construction process has been extensively studied in the literature and, thus, in this work we use similar technique to the one proposed in [6]. Due to space constraints, we briefly sketch the tree construction procedure as follows: Each node connected to a CP periodically broadcasts ADV messages to its neighbors. These messages are used by neighbors to compute the $\alpha$ values and, thus, choose their parent nodes. To join a parent node $v_j$, a node $v_i$ sends a JOIN message to node $v_j$. When $v_j$ receives this message, it adds $v_i$ to its list of children and sends back an ACCEPT message to $v_i$. The addition of this extra node may alter the characteristics if the branch (may results in decreased $\alpha$ values). It is thus possible for a neighbor $v_k$ which depends on the same parent ($v_j$) to find an alternative branch with a better route to a CP. In this case, node $v_k$ attempts to join the alternative branch (JOIN/ACCEPT procedure), if successful, $v_k$ leaves its current parent (i.e., branch) by sending a LEAVE message to $v_j$. Nevertheless, route changes in a WiMAX mesh are not frequent, since the nodes are static in most applications especially when they are used to extend coverage. The routing tables are updated in the nodes by exchanging additional messages, namely RT_ADD and RT_DEL. The former is used upwards from leaves to the CP when a new node joins a branch, while the latter deletes a node from a branch after the reception of a LEAVE message.

### B. Rate Assignment

Once the tree is constructed, the video rate at each node must be determined. This procedure is centralized on a management platform and relies on our algorithm presented in our previous work [16]. For space constraints, we only sketch the main idea of the proposed algorithm and refer the reader to our previous work for more details. The algorithm consists of computing the number of flows that pass through each branch of the tree and then to assign a capacity to each branch that is proportional to this quantity.

For instance, in Fig. 2, there are a total of 6 flows in the tree with a total uplink capacity of $C$. The left branch that deliver 3 flows is assigned a capacity of $\frac{C}{2}$ , while the middle branch with 2 flows gets $\frac{C}{3}$. We then check whether this amount of bandwidth is large enough to accommodate the video flows (i.e., $> W_{min}$). If not, the number of flows that passes through the branch is reset to zero and the capacity assigned to this branch is released. It means that the cameras (flows) that pass through this branch will have to be put offline in this critical situation where there is not enough available bandwidth (Of course, we expect that an alarm will be displayed in order for the human operator to be aware of this situation. As a result, the configuration of priorities of the different cameras can be changed accordingly). The capacity of this branch is redistributed to the neighboring branches. For instance, in Fig. 2, imagine that $\frac{C}{6} < W_{min}$ so that the video flow of the right branch has to be stopped. The flow counts are modified accordingly and the neighboring branches are assigned $\frac{3}{5}C$ and $\frac{2}{5}C$, respectively. Similarly, this capacity pre-assignment must also be compared to the physical capacity upper bound of each

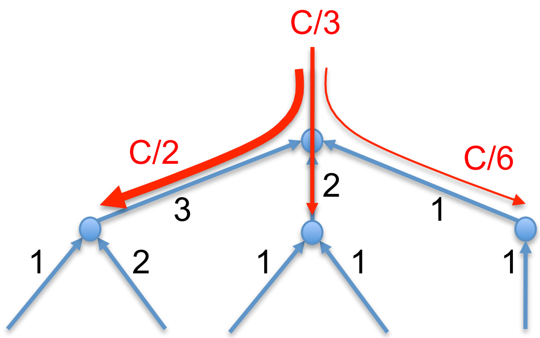



Figure 2. Basic principle of the rate assignment algorithm.

branch (i.e., $L_{ij}$). When the assigned amount of capacity is too large to be accommodated by the branch, it is then adjusted and the remaining capacity is assigned to the neighboring branches. This procedure is repeated iteratively from the tree roots (CPs) towards its leaves. When several priorities are available (we consider two priority levels in this work, namely high and low), the algorithm starts with the highest level of priority. The remaining bandwidth is then shared by the nodes with lower level of priority by running a new instance of the algorithm and so on.

## V. Performance Evaluation

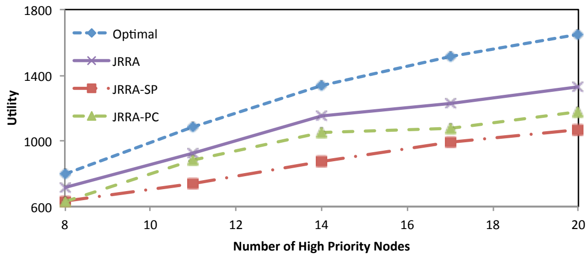
To validate the performance of the proposed scheme, we have conducted an extensive set of experiments using a dedicated C++ coded simulator. We compare the performance of our proposals to the optimal solution, obtained by solving the ILP presented in Section III-B using a commercial version of AMPL and CPLEX. Since the running time required to obtain the optimal solution increases exponentially with the number of nodes in the network, comparison with optimal result is only possible when the problem scale is small. Therefore, in this section we limit the number of nodes to 40.

Moreover, to benchmark our routing algorithm, we compare it to two other routing algorithms, namely *shortest-path* routing (termed as JRRA-SP) and *path-capacity* routing (termed as JRRA-PC). The former enables a node to reach the wired network (through a CP) using the minimum number of hops, but does nothing to balance network load. The latter works by constructing the best path capacity spanning tree(s), it represents the best physical (i.e., raw) capacity of the path that connects a node to the wired network. Path capacity assumes that the bottleneck of a path can be constituent link on the path.

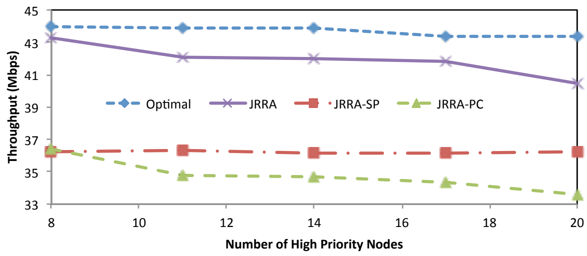
In the simulations, we generate random topologies with nodes deployed in a 1000 x 1000 $m^2$ terrain. We randomly placed 3 CPs in the simulated region. The cell capacity is fixed at $C = 20$ Mbps. The transmission range $R_T$ is 200 m. The minimum acceptable video data rate generated by each camera $W_{min}$ is 768 Kbps (i.e., $R_{min}$) and $W_{max}$ is fixed at 4608 Kbps. We partitioned the links in decreasing order in terms of their physical length into three sets and assign the links in these three sets with capacity of 2, 5 and 8 Mbps, respectively. Priority $P$ is set to 1 for low priority cameras and 100 for high priority ones. We monitored the average utility per camera of the video surveillance system. The minimum utility of each accepted camera $U_{min} = 1$ and $U_{step} = 1/5$. Also, the utility for video transmission rate below $R_{min}$ (i.e., 768 Kbps) is considered to be insignificant, hence, we decided to put the camera offline. Utility for each offline camera is assumed to be zero. For all simulation results in this paper, each experiment is an average of 5 different random topologies, and we are interested in evaluating (1) utility, (2) throughput, (3) quality of received video data, and (4) number of accepted traffic sources (i.e., cameras) in the network.

**Utility and Throughput:** To study the impact of number of high priority nodes (cameras) on the network performance, we consider random graphs with average node degree of 5. We vary the number of high priority nodes from 8 to 20. Other settings are as presented above. We can clearly see in Fig. 3(a) that all schemes experience a linear utility increase with the increase of high priority nodes. This is because as more high priority nodes deployed all proposed schemes will try to accommodate as many of them as possible at the best possible data rate, which yield a better utility. Fig. 3(b) shows the throughput with respect to the number of high priority nodes in the network. No matter what the high priority nodes number is, it shows the throughput of all schemes remains nearly constant. This is because all schemes first try to allocate the highest rate to the high priority nodes, after, if more bandwidth still available they will allocate it to low priority nodes, and thus, the whole network will attain the same throughput regardless the priority and importance of the nodes. It is interesting to note that our scheme consistently yields a better performance than shortest-path and path-capacity routing. It is worth mentioning that although sometimes the shortest-path routing does not necessarily indicate higher network throughput, which is true in most cases, it performs similar to JRRA-PC in terms of throughput in this experiment. This is because shorter links can support higher data rates (capacity). It is often possible to obtain higher throughput by multi-hopping since higher data rates are used. As the distance increases, more robust burst profiles (modulation and coding techniques) are needed to reduce bit error rate (BER) which results in lower data rate. For instance, 64 QAM3/4 can ensure almost 11 Mbps for 1.5 km. QPSK1/2 can offer 2 Mbps at 5 km [10].

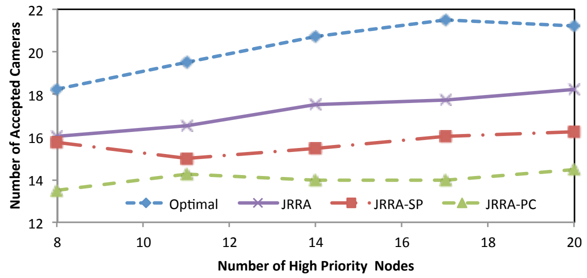
**Accepted Traffic Sources:** Figure 3(c) shows how well the JRRA scheme performs compared to the optimal solution in terms of number of accepted traffic sources (i.e., cameras) in the resulting routing trees. As can be seen from the graphs, the JRRA reacts smoothly and consistently as the number of high priority nodes increases. It is clear that, as the number of high priority nodes increased, all schemes experience an improve in the number of accepted cameras. In other words, as we increase the number of high priority nodes deployed in the network, the proposed solution tries to accept as many of them as possible with best data rate.




(a) Network Utility




(b) Total Throughput




(c) Number of accepted Cameras

Figure 3. Network performance as a function of number of high priority nodes.

## VI. Conclusion and Future Work

This paper addresses the problem of guaranteed transmission of video flows in the context of WiMAX mesh networks for video surveillance purposes. In such video surveillance systems, a key design requirement is that video quality must not fall below a certain limit to be exploited. In the standard system, when the effective throughput drops, data rate for all the cameras, regardless their importance, drops equally and the utility of the whole video surveillance system drops significantly. In critical situations where the available throughput in the system may not be sufficient to accommodate the streaming video data from all the cameras, we proposed a novel cross-layer solution that decides which camera(s) to put offline so that overall utility of, especially the high priority cameras, whole video surveillance system improves. In particular, we have presented a near optimal Joint Routing and Rate Assignment scheme, termed JRRA, to maximize the utility of WiMAX surveillance system with QoS guarantee. We further formulated the problem as Integer Linear Program (ILP) and gave solution to it. Simulation results have been presented to illustrate the performance of the proposed approach.

The results presented in this paper indicate the gains achievable under ideal channel conditions with no transmission errors, future work will be necessary to characterize the claims under non-ideal channels.

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