

# Quality-Aware Coding and Relaying for 60 GHz Real-Time Wireless Video Broadcasting

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**Abstract**—Wireless streaming of high-definition video is a promising application for 60 GHz links, since multi-Gigabit/s data rates are possible. In particular we consider a sports stadium broadcasting system where video signals from multiple cameras are transmitted to a central location. Due to the high pathloss of 60 GHz radiation over the large distances encountered in this setting, the use of relays is required. This paper designs a quality-aware coding and relaying algorithm for maximization of the overall video quality. We consider the setting that the source can split its data stream into parallel streams, which can be transmitted via different relays to the destination. For this, we derive the related formulation and re-formulate it as convex programming, which can guarantee optimal solutions.

**Index Terms**—60 GHz, Multi-Gbit/s HD Video Streaming, Wireless Video Quality Maximization, Relaying

## I. INTRODUCTION

Wireless video streaming in the millimeter-wave range has received a lot of attention in both the academic and industrial communities. In particular the 60 GHz frequency range is of great interest: around 7 GHz bandwidth (58-65 GHz) has been made available, which enables multi-Gbit/s high-definition video streaming in an uncompressed, or less compressed, manner. Therefore, two industry consortia, i.e., WirelessHD [1] and Wireless Gigabit Alliance (WiGig) [2], have developed related specifications; there are also two activities within the IEEE, namely IEEE 802.15.3c [3] and IEEE 802.11ad [4], for such 60 GHz systems.

In this paper, we design and analyze such a 60 GHz video transmission system for outdoor applications, in particular in a sports stadium. In this system, there are multiple wireless video cameras in a stadium for high-quality real-time broadcasting, all send their signals to a broadcasting center. To transmit uncompressed HD video streams in real-time, a data rate of around 1.5 Gbit/s is required [5]. Since the distance between wireless cameras and a broadcasting center is on the order of several hundred meters, the high pathloss at 60 GHz is one of key challenges that limits communication ranges. One promising approach to deal with this problem is using *relays* for extending the coverage [5]. Increasing the number

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TABLE I  
RELATED WORK

	Route Selection	Rate Control	Multi-Beam	60 GHz Channel	Video Streams
[5]	○	○	×	○	○
[7]	○	×	○	×	×
[8]	○	○	○	×	×
[9]	○	×	×	×	○
[10]	○	×	×	×	○
[11]	○	×	×	×	○
[12]	○	○	×	×	×

of relays obviously improves performance, but also increases costs. Therefore, we are interested in observing the tradeoff between performance and number of relays. Additionally, we take the complexity of the antennas into account. In order to compensate for the high pathloss, as well as to reduce interference, high-gain antennas need to be employed. We also consider the situation where the antenna at the camera (video source) can form multiple beams, so that it can split its data stream into multiple streams and send them to the destination via parallel links. In this case, appropriate compression and routing of multiple streams via the same relay can be used.

Relaying for sum rate maximization has been analyzed in many papers. However, for video streaming, we are more interested in *video quality*. For this, the proposed quality-aware formulation selects the relays and decides the coding rates for every single video stream. With this formulation, optimal solutions are obtained by convex optimization techniques.

The remainder of this paper is organized as follows: Section II gives an overview of related work. Section III explains the details of our outdoor sports broadcasting system using 60 GHz links. Section IV presents the proposed quality-aware coding and relaying algorithm for maximizing the delivered video qualities. Section V evaluates the performance and then section VI concludes this paper. Additional results and scenarios can be found in the (submitted) journal version of this paper [6].

## II. RELATED WORK

There are two salient factors in our broadcasting setup: (i) stream splitting via the multiple-beam antennas, and (ii) rate control for video quality maximization. In the following, we outline why these aspects make the setup different from other scenarios that have been treated in the literature.

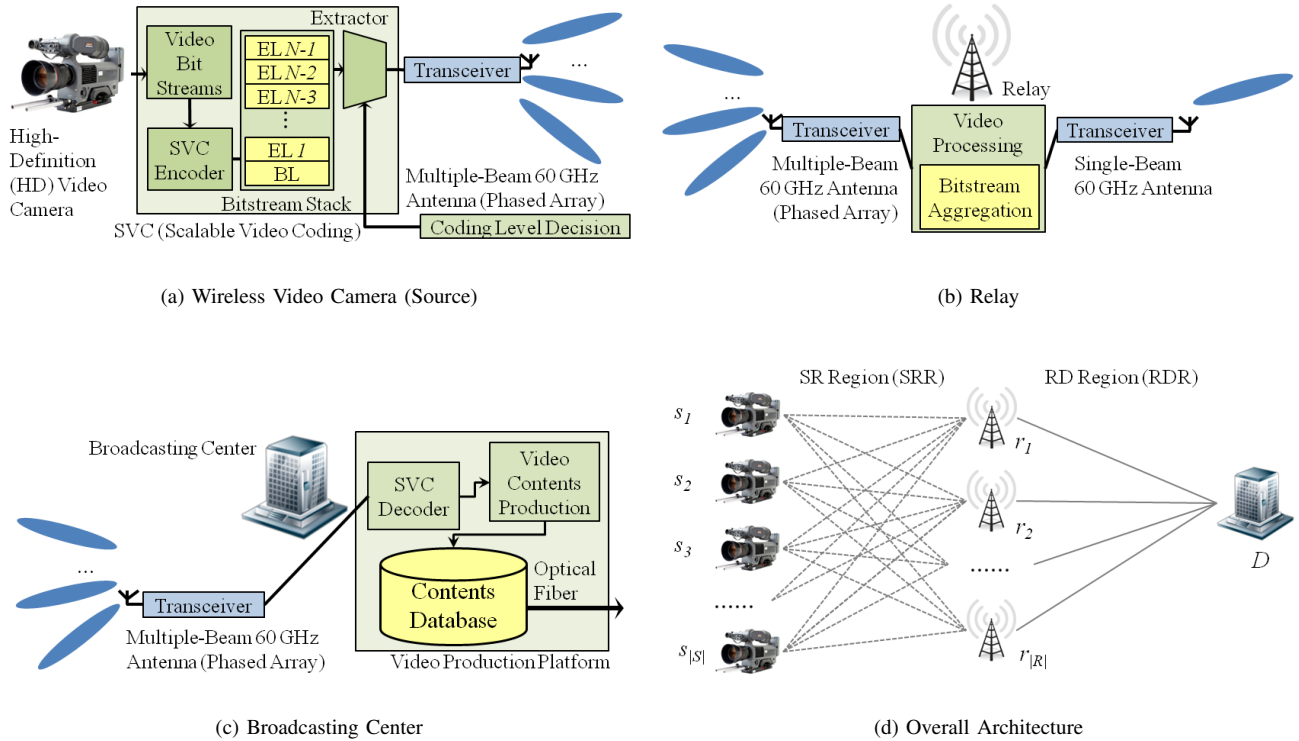


Fig. 1. System Components (Camera (a), Relay (b), Broadcasting Center (c)) and An Overall Architecture (d)

There is, of course, a huge number of papers (too numerous to reference here) dealing with the topic of routing (relay selection) and sum rate maximization in multi-node networks with multi-beam relays [7] and with multi-beam sources and relays [8]. However these papers do not consider the control of the video coding rate (compression), and are thus not directly applicable to our scenario.

For video networks, example publications include [9], [10], [11]. The scheme in [9] is for video streaming over IEEE 802.11 networks. The proposed scheme is efficient for the multi-hop networks it investigates; however, it does not consider the video stream splitting via the multi-beam antennas and route selection. Ref. [10] considers video streaming in multi-hop networks. It considers networks similar to ours (when specialized to the two-hop case), but again does not investigate multi-beam antennas and the splitting of the data streams. The formulation in [11] considers path selection for video streaming in MANET. It concentrates on the consideration of interference, a factor that does not play a role in our 60 GHz channel, where the high directionality of the links prevents inter-stream interference. None of these papers consider the control of the coding rate (compression).

In previous research on video streaming, schemes usually considered multipath transmission to combat the limited bandwidth [10][11]. Also, some of the research considered retransmission of frames and tried to reduce transmission time [9]. However, thanks to the extremely large bandwidth at 60 GHz, these factors are not longer critical in our system.

The representative work which considers both rate control and routing appeared in [12]: However, the relays cannot

aggregate streams, which is required when the number of relays is smaller than the number of flows. In addition, the proposed framework does not consider the properties of video. In our previous work [5], we considered the properties of 60 GHz channel, rate control, and video quality, but we restricted ourselves to the cases that the number of relays exceeds the number of sources (i.e., no consideration for multi-beam antennas) and the numbers of sources and destinations are identical.

The comparison results of selected related work is summarized in Table I.

We finally note that wireless video for sports stadiums discussed in [13]; however the fundamental setup differs from ours in that [13] considers content distribution to wireless devices of the audience in the stadium, while our system is for real-time streaming to a broadcasting center in the stadium.

### III. A REFERENCE SYSTEM ARCHITECTURE

#### A. Link Budget Analysis

A link budget analysis provides the tradeoff between data rate and achievable range [13][14]. Here, Shannon's equation for the capacity is used for the data rate:

$$C = B \cdot \log_2(1 + \text{SNR}) \quad (1)$$

where SNR is equal to  $P_{\text{signal}}/P_{\text{noise}}$  on a linear scale,  $P_{\text{signal}}$  and  $P_{\text{noise}}$  stand for the signal power and noise power, and  $B$  stands for bandwidth (2.16 GHz in WiGig [4]). The signal power expressed in dB,  $P_{\text{signal,dB}}$ , is obtained as:

$$P_{\text{signal,dB}} = E + G_r - W - O(d) + F(d) \quad (2)$$

where  $E$  denotes the EIRP (equivalent isotropically radiated power), which is limited to 40 dBm in the USA and 57 dBm in Europe.  $G_r$  means the receiver antenna gain and is set to 40 dB, which corresponds to commercially high-gain 60 GHz scalar horn antennas [15], which we propose to achieve long range.  $W$  presents the shadowing margin and is set to 10 dB.  $F(d)$  is the mean pathloss, which depends on the distance  $d$  between transmitter and receiver

$$F(d) = 10 \log_{10} \left( \frac{\lambda}{4\pi d} \right)^n \quad (3)$$

where the pathloss coefficient  $n$  is set to 2.5 [16] and the wavelength ( $\lambda$ ) is 5 millimeter at 60 GHz.  $O(d)$  denotes the oxygen attenuation, which can be computed as  $O(d) = \frac{15}{1000}d$  when  $d > 200$  m. Otherwise, it is ignored [16]. The noise power in dB,  $P_{\text{noise,dB}}$  is computed as:

$$P_{\text{noise,dB}} = 10 \log_{10} (k_B T_e \cdot B) + F_N \quad (4)$$

where  $k_B T_e$  stands for the noise power spectral density ( $-174$  dBm/Hz) and  $F_N$  is the noise figure of the receiver (6 dB). By combining the above equations, it is easy to find that approximately 200 – 300 m is the maximum distance for obtaining 1.5 GBit/s data rate, i.e., successful uncompressed video transmission.

### B. 60 GHz Outdoor Broadcasting Systems

As shown in Sec. III-A, the assistance of relays is required if the distance between wireless cameras and a broadcasting center is more than 200 – 300 m. Furthermore, the size of a sports stadium (from wireless cameras to a broadcasting center) is not more than 500 m (e.g., the long side of the Los Angeles Memorial Coliseum is approximately 300 m.). Thus, we restrict the number of relays to one. In our 60 GHz broadcasting system, three components are existing, i.e., wireless video cameras, relays, and a broadcasting center. As presented in Fig. 1(a), the proposed wireless video cameras have scalable video coding (SVC) functionalities that reproduce the recorded video signals as layered SVC-coded bitstreams. If the achievable rate of a 60 GHz link is sufficient for uncompressed video streaming (i.e., more than 1.5 Gbit/s), all layers can be transmitted. Otherwise, the optimal coding level decision module has to determine the number of layers. Each wireless video camera has multiple-beam antennas. Therefore, each antenna can form  $N$  independent beams, so that the multiple streams created by SVC-encoding are divided into  $N$  parts and each part is assigned to a beam to be concurrently transmitted. We furthermore assume that the relays have multiple-beam antennas for reception, see Fig. 1(b). The relays aggregate the received signals and transmit them towards a broadcasting center. As presented in Fig. 1(c), the proposed broadcasting center has multiple antennas which are facing the relays. We emphasize that due to the narrow beamwidth ( $1.5^\circ$ - $10^\circ$  [15]) of the antennas, multiple streams arriving at the broadcasting center do not interfere with each other (similarly for the relays).

### C. Objective

For this given system in Sec. III-B, our objective is the maximization of the delivered total video quality (not the sum rate maximization), then the relationship between the video qualities and data rates should be defined. As shown in [6][17], the quality of video is related to the data rate in a nonlinear fashion as a sublinearly, but monotonically, increasing form. This form is defined as  $f_q(\cdot)$  in the mathematical formulation (Sec. IV). Following is one example of a possible quality index function:

$$f_q(a) = \frac{1}{\log_\beta(a_{\max} + 1)} \log_\beta(a + 1) \quad (5)$$

$\beta$  is a base ( $1 < \beta$ ),  $a_{\max}$  is a desired data rate for uncompressed video streaming, and  $a$  is a given data rate.

For interactive TV, where users can select the camera view they prefer, it is desirable to additionally impose constraints on the minimum quality for each camera.

## IV. MATHEMATICAL FORMULATION OF OPTIMIZATION PROBLEM

Fig. 1(d) shows the reference model with a set of sources  $\mathcal{S}$ , a set of relays  $\mathcal{R}$ , and a single destination  $D$ . In the relay-destination region (RDR) of Fig. 1(d), all relays are connected to  $D$ . Then the maximum achievable rates of all relay and destination pairs can be computed (i.e.,  $a_{r_1 \rightarrow D}^{\text{RDR}}, \dots, a_{r_{|\mathcal{R}|} \rightarrow D}^{\text{RDR}}$ ). Our assumption is that  $D$  can form a sufficient number of independent beams so that it has no limitations concerning the number of relays. Thus, we wish to find optimal combinations between sources and relays in source-relay region (SRR) for the settings that both sources and relays can form multiple beams. Then, our formulation for the maximization of delivered total video quality is as follows:

$$\max \sum_{j=1}^{|\mathcal{R}|} \sum_{i=1}^{|\mathcal{S}|} f_q \left( \frac{1}{2} a_{s_i \rightarrow r_j}^{\text{SRR}} \right) x_{s_i \rightarrow r_j}^{\text{SRR}} \quad (6)$$

subject to

$$\sum_{i=1}^{|\mathcal{S}|} a_{s_i \rightarrow r_j}^{\text{SRR}} x_{s_i \rightarrow r_j}^{\text{SRR}} \leq \mathcal{A}_{r_j \rightarrow D}^{\text{RDR}}, \forall j, \quad (7)$$

$$\sum_{i=1}^{|\mathcal{S}|} x_{s_i \rightarrow r_j}^{\text{SRR}} \leq B_{r_j}, \forall j, \quad (8)$$

$$\sum_{j=1}^{|\mathcal{R}|} x_{s_i \rightarrow r_j}^{\text{SRR}} \leq B_{s_i}, \forall i, \quad (9)$$

$$\underline{a}_{s_i} \leq \sum_{j=1}^{|\mathcal{R}|} a_{s_i \rightarrow r_j}^{\text{SRR}}, \forall i, \quad (10)$$

$$a_{s_i \rightarrow r_j}^{\text{SRR}} \leq \mathcal{A}_{s_i \rightarrow r_j}^{\text{SRR}}, \forall i, \forall j, \quad (11)$$

$$x_{s_i \rightarrow r_j}^{\text{SRR}} \in \{0, 1\}, \forall i, \forall j, \quad (12)$$

$$x_{r_j \rightarrow D}^{\text{RDR}} = 1, \forall j, \quad (13)$$

where the used notations are listed in Table II. If  $s_i$  and  $r_j$  are connected, then  $x_{s_i \rightarrow r_j}^{\text{SRR}}$  is 1 by (12). Otherwise,  $x_{s_i \rightarrow r_j}^{\text{SRR}}$  is 0 by (12). The relays are all connected to  $D$ , thus,  $x_{r_j \rightarrow D}^{\text{RDR}} = 1$

TABLE II  
NOTATIONS USED IN MATHEMATICAL FORMULATION

Notation	Description
$\mathcal{S}$	Set of sources
$\mathcal{R}$	Set of relays
$D$	Destination
$s_i$	Source $i$ , $\forall i \in \{1, \dots,  \mathcal{S} \}$
$r_j$	Relay $j$ , $\forall j \in \{1, \dots,  \mathcal{R} \}$
$\mathcal{A}_{s_i \rightarrow r_j}^{\text{SRR}}$	Max achievable rate between $s_i$ and $r_j$
$\mathcal{A}_{r_j \rightarrow D}^{\text{RDR}}$	Max achievable rate between $r_j$ and $D$
$a_{s_i \rightarrow r_j}^{\text{SRR}}$	Data rate between $s_i$ and $r_j$
$x_{s_i \rightarrow r_j}^{\text{SRR}}$	Connectivity index between $s_i$ and $r_j$
$\underline{a}_{s_i \rightarrow r_j}^{\text{SRR}}$	Lower bounds of rates at each source $s_i$ for minimum required video quality
$f_q(\cdot)$	Function for the relationship between video quality and data rate
$B_{s_i}$	Number of antenna-beams at $s_i$
$B_{r_j}$	Number of antenna-beams at $r_j$

as shown in (13). The  $\mathcal{A}_{s_i \rightarrow r_j}^{\text{SRR}}$  and  $\mathcal{A}_{r_j \rightarrow D}^{\text{RDR}}$  are maximum achievable rates computed by (1). In addition, the desired data rates between  $s_i$  and  $r_j$  are less than  $\mathcal{A}_{s_i \rightarrow r_j}^{\text{SRR}}$  as shown in (11) where  $f_q(\cdot)$  is a function for the relationship between video quality and data rate (logarithmically and monotonically increasing form). As shown in (10), the desired data rates between  $s_i$  and  $r_j$  should exceed the defined minimum rates ( $\underline{a}_{s_i}$ ,  $\forall s_i$  and  $\forall r_j$ ), which are minimum data rates for guaranteeing the required minimum video qualities for each flow. Here,  $\mathcal{A}_{s_i \rightarrow r_j}^{\text{SRR}}$  from  $s_i$  to  $r_j$  and  $\mathcal{A}_{r_j \rightarrow D}^{\text{RDR}}$  from  $r_j$  to  $D$  are fixed. For each individual source, there are multiple outgoing flows (multiple beams) toward relays, as formulated in (9) where  $B_{s_i}$  stands for the number of antenna-beams at source  $i$ ,  $\forall i \in \{1, \dots, |\mathcal{S}|\}$ . Similarly, each relay can form multiple beams in receiving mode, thus the number of incoming flows from sources can be  $B_{r_j}$  as formulated in (8) where it means the number of antenna-beams at relay  $j$ ,  $\forall j \in \{1, \dots, |\mathcal{R}|\}$ . In (7), for each relay, the summation of incoming rates from sources cannot exceed the data rate between the relay and  $D$ . Finally, (6) describes the objective of finding the pairs between sources and relays as well as finding the corresponding data rates for maximizing the total video quality and the data rate value becomes  $1/2$  due to the half-duplex constraint.

The proposed formulation is a non-convex mixed-integer nonlinear program (MINLP) as shown in Theorem 1.

**Theorem 1.** *The formulation in Section IV is non-convex.*

*Proof:* If there exists a quality function which is logarithmically and monotonically increasing, then the corresponding formulation is a non-convex MINLP. This proof considers the setting of one-source and one-relay (the simplest case). Then the objective function becomes

$$\begin{aligned} f\left(a_{s_i \rightarrow r_j}^{\text{SRR}}, x_{s_i \rightarrow r_j}^{\text{SRR}}\right) &\triangleq f_q\left(a_{s_i \rightarrow r_j}^{\text{SRR}}\right) x_{s_i \rightarrow r_j}^{\text{SRR}} \\ &= \mathcal{K} \log_{\beta}\left(a_{s_i \rightarrow r_j}^{\text{SRR}} + 1\right) x_{s_i \rightarrow r_j}^{\text{SRR}} \end{aligned} \quad (14)$$

where  $\mathcal{K} = \frac{1}{\log_{\beta}(a_{\max} + 1)}$  is constant. To show that this is non-

convex, the second-order Hessian of this should not be positive definite [18]. The Hessian  $\nabla^2 f\left(a_{s_i \rightarrow r_j}^{\text{SRR}}, x_{s_i \rightarrow r_j}^{\text{SRR}}\right)$  is:

$$\begin{bmatrix} 0 & \frac{\mathcal{K}/\ln \beta}{a_{s_i \rightarrow r_j}^{\text{SRR}} + 1} \\ \frac{\mathcal{K}/\ln \beta}{a_{s_i \rightarrow r_j}^{\text{SRR}} + 1} & -x_{s_i \rightarrow r_j}^{\text{SRR}} \cdot \frac{\mathcal{K}/\ln \beta}{\left(a_{s_i \rightarrow r_j}^{\text{SRR}} + 1\right)^2} \end{bmatrix} \quad (16)$$

and then the corresponding two eigenvalues are

$$\frac{\mathcal{I}}{2} \pm \frac{1}{2} \sqrt{\mathcal{I}^2 + \left(\frac{2\mathcal{K}/\ln \beta}{a_{s_i \rightarrow r_j}^{\text{SRR}} + 1}\right)^2} \quad (17)$$

where  $\mathcal{I} = \frac{-\mathcal{K}}{\ln \beta} \cdot \frac{x_{s_i \rightarrow r_j}^{\text{SRR}}}{\left(a_{s_i \rightarrow r_j}^{\text{SRR}} + 1\right)^2}$ ,  $0 \leq a_{s_i \rightarrow r_j}^{\text{SRR}} \leq 1.5$ ,  $0 \leq x_{s_i \rightarrow r_j}^{\text{SRR}} \leq 1$ .

These are not all positive, thus Hessian is not positive definite, which proves the formulation is non-convex. ■

For non-convex MINLP, heuristic searches can find approximate solutions but cannot guarantee optimality [18]. With the following Theorem, our non-convex MINLP can be reformulated as a convex program form.

**Theorem 2.** *For the given non-convex MINLP formulation in Section IV, introducing*

$$a_{s_i \rightarrow r_j}^{\text{SRR}} \leq \mathcal{A}_{s_i \rightarrow r_j}^{\text{SRR}} \cdot x_{s_i \rightarrow r_j}^{\text{SRR}}, \forall i, \forall j \quad (18)$$

*instead of (11) makes the formulation a convex program.*

*Proof:* For the non-convex MINLP formulation in Section IV,  $x_{s_i \rightarrow r_j}^{\text{SRR}} = 0$  means the link is disconnected. Thus the corresponding rate becomes 0 and (18) leads to the same result when  $x_{s_i \rightarrow r_j}^{\text{SRR}} = 0$ , i.e.,

$$a_{s_i \rightarrow r_j}^{\text{SRR}} \leq \underbrace{\mathcal{A}_{s_i \rightarrow r_j}^{\text{SRR}}}_{0} \cdot 0, \forall i, \forall j. \quad (19)$$

Otherwise, if  $x_{s_i \rightarrow r_j}^{\text{SRR}} = 1$ , then this term is equivalent to (11). Therefore, in turn, (6) is also updated as

$$\max \sum_{j=1}^{|\mathcal{R}|} \sum_{i=1}^{|\mathcal{S}|} f_q\left(\frac{1}{2} a_{s_i \rightarrow r_j}^{\text{SRR}}\right) \quad (20)$$

and (7) is also updated:

$$\sum_{i=1}^{|\mathcal{S}|} a_{s_i \rightarrow r_j}^{\text{SRR}} \leq \mathcal{A}_{r_j \rightarrow D}^{\text{RDR}}, \forall j. \quad (21)$$

Then now there are no non-convex terms in the program<sup>1</sup>. ■

Finally, our convex MINLP, which can guarantee optimal solutions, is as follows: (20) subject to (21), (8), (9), (18), (10), (12), (13) where  $\forall i \in \{1, \dots, |\mathcal{S}|\}$ ,  $\forall j \in \{1, \dots, |\mathcal{R}|\}$ .

## V. PERFORMANCE EVALUATION

To verify the superior performance of our scheme, i.e., *video quality maximization* (named as VQM), we compare it with the following two schemes:

- The joint video coding and relaying under the consideration of *sum rate maximization* (named as SRM). In this

<sup>1</sup>It is trivial that the weighted summation of convex (or concave) terms are also convex (or concave).

TABLE III  
EXPECTATION OF ACHIEVED NORMALIZED AGGREGATED VIDEO QUALITY

			Multiple-Beams at $s_i$ and $r_j$		
$ \mathcal{S} $	$ \mathcal{R} $	Setting	VQM	SRM	JRSR
5	10	I	4.166	3.873	3.331
5	10	II	4.934	4.647	4.165
5	10	III	4.681	4.397	3.632
10	5	I	4.164	3.871	3.352
10	5	II	4.954	4.620	4.182
10	5	III	4.664	4.371	3.650
10	10	I	8.813	8.451	5.483
10	10	II	9.817	9.452	6.336
10	10	III	9.312	8.958	5.795
10	15	I	8.883	8.574	5.633
10	15	II	9.872	9.563	6.456
10	15	III	9.383	9.074	5.927
15	10	I	13.420	11.765	6.483
15	10	II	14.902	13.255	7.376
15	10	III	14.403	12.755	6.839

case, the proposed objective function (20) is:

$$\max \sum_{j=1}^{|\mathcal{R}|} \sum_{i=1}^{|\mathcal{S}|} \frac{1}{2} a_{s_i \rightarrow r_j}^{\text{SRC}} \quad (22)$$

due to the fact that the quality is no longer considered.

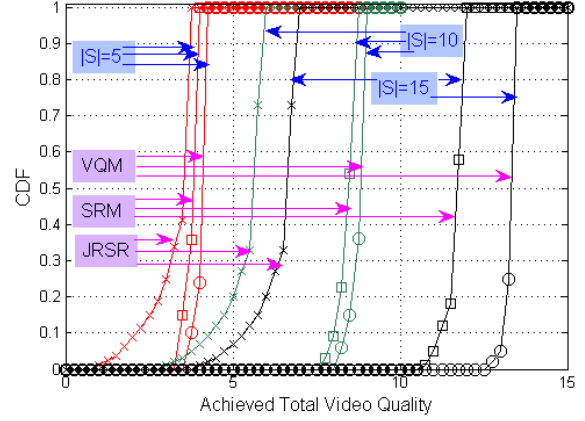
- The scheme in [12], which is an efficient algorithm that considers joint rate selection and routing (named as JRSR). For fair comparisons, we adapt the scheme to our outdoor-stadium architecture (one-tier relay) and allow only decode-and-forward relaying. Lastly, the number of sources is equal to the number of destinations in [12].

For the setting, the cameras are uniformly distributed on top of the stadium. Between stadium and broadcasting center, multiple relays are uniformly deployed along a line. To vary the settings, we consider this line to be near the cameras (Setting I), in the middle between cameras and broadcasting center (Setting II), and near the center (Setting III).

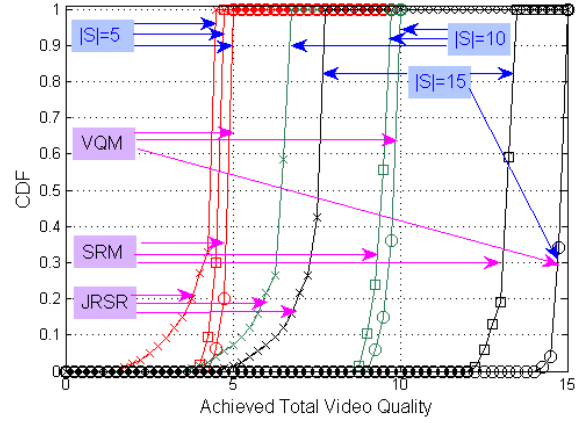
As our performance measure, we consider the cumulative probability distribution (cdf) of the aggregate video quality. The cdf is obtained as follows: we consider multiple realizations of the deployment of sources and relays, i.e., the random deployment of relays with Setting I, Setting II, and Setting III. For each such realization, we optimize coding rates and relay selection; thus each run gives us one realization of the aggregate video quality. We finally plot the cdf of this quality. For the simulation of VQM, the lower bounds ( $a_{s_i}$ ,  $\forall i \in \{1, \dots, |\mathcal{S}|\}$ ) of each source are set as 0.75 Gbit/s (50% of 1.5 Gbit/s).

#### A. CDF of Aggregate Video Quality

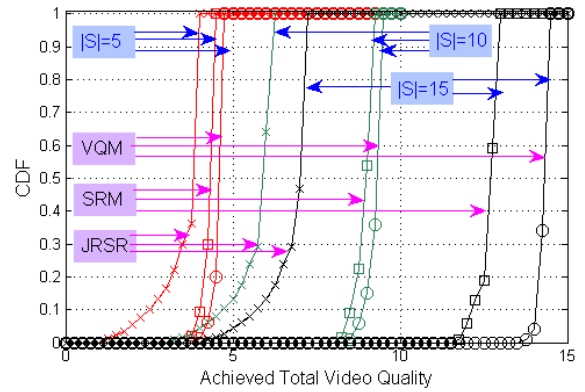
Fig. 2 plots the cases that the number of sources is smaller, equal, or larger than the number of relays (i.e.,  $|\mathcal{S}| = 5, 10, 15$ , and  $|\mathcal{R}| = 10$ ). The mean achieved normalized aggregated



(a) Setting I



(b) Setting II



(c) Setting III

Fig. 2. Simulation Results: Number of Sources ( $|\mathcal{S}| = 5, 10, 15$ ) and Fixed Number of Relays ( $|\mathcal{R}| = 10$ )

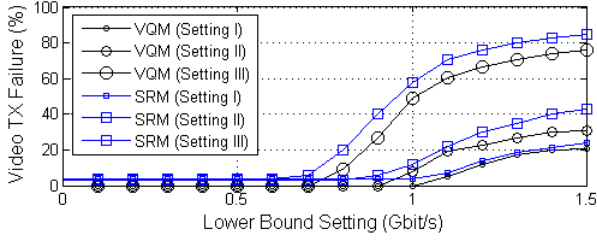


Fig. 3. Impact of Various Lower Bound Setting:  $|\mathcal{S}| = 10$ ,  $|\mathcal{R}| = 15$

video qualities are in Table III. In Table III, the video quality values from each source are normalized as 1 for performance evaluation. Thus, if we have  $N$  cameras in the system, the maximum achievable aggregated video quality is  $N$ .

As shown in this result, the performance of JRSR is worse than that of both SRM and VQM. The latter (i.e., JRSR), by design, does not allow the exploitation of the multiple-beam antennas at relays, and thus shows worse performance. The performance gains of SRM are more pronounced than JRSR in Settings I and III, i.e., when the relays are close to either the sources or the destination. More importantly, we find that the relative performance advantage drastically increases as the number of sources increases relative to the number of relays. This is not surprising, as for these situations the ability of the sources to split their streams and flexibly route them via the relays becomes more important.

We also see that SRM shows lower performance than VQM due to the fact that SRM aims to the maximization of sum data rates, while VQM aims to maximize the overall delivered video quality. The relative advantage of VQM also increases as the number of sources increases. Again, this is not surprising, as the bandwidth limitations become more stringent as the number of sources increases.

In conclusion, our proposed VQM eventually achieves the best performance than SRM and JRSR.

### B. Impact of Lower Bound Setting

In previous simulation, the lower bounds for the data rate per data stream are set as 0.75 Gbit/s. Here, we vary this value from 0 Gbit/s (no lower bound) to 1.5 Gbit/s (allowing only uncompressed video) in steps of 0.1 Gbit/s. As a performance quality measure, we define “stream outage” (i.e., the probability that at least one stream does not have the minimum required quality). As shown in Fig. 3, Setting III suffers significantly from the higher required per-stream quality. With Setting III, the data rates between sources and relays are lower than the others. Thus, when we set the lower bound quite high, all flows are disconnected. Thus, it achieves the lowest performance. On the other hand, in Setting I, all flows between sources and relays have enough capacity to support uncompressed video transmission, thus, a higher setting for minimum quality does not have a strong impact. Fig. 3 also shows that VQM has better performance than SRM for all settings.

## VI. CONCLUSION

This paper suggests and discusses quality-aware coding and routing for 60 GHz multi-Gbit/s real-time video streaming in an outdoor broadcasting system. In the system, there are multiple wireless video cameras distributed throughout the stadium. We presented an optimization framework for finding the combination of wireless link pairs between wireless cameras and relays that can maximize the overall or per-flow qualities of delivered video to a broadcasting center. An initial non-convex MINLP description is re-formulated as a convex program, which allows optimum solutions. Simulations show that this methodology significantly outperforms other methods that do not take the peculiarities of millimeter-wave video links into account.

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