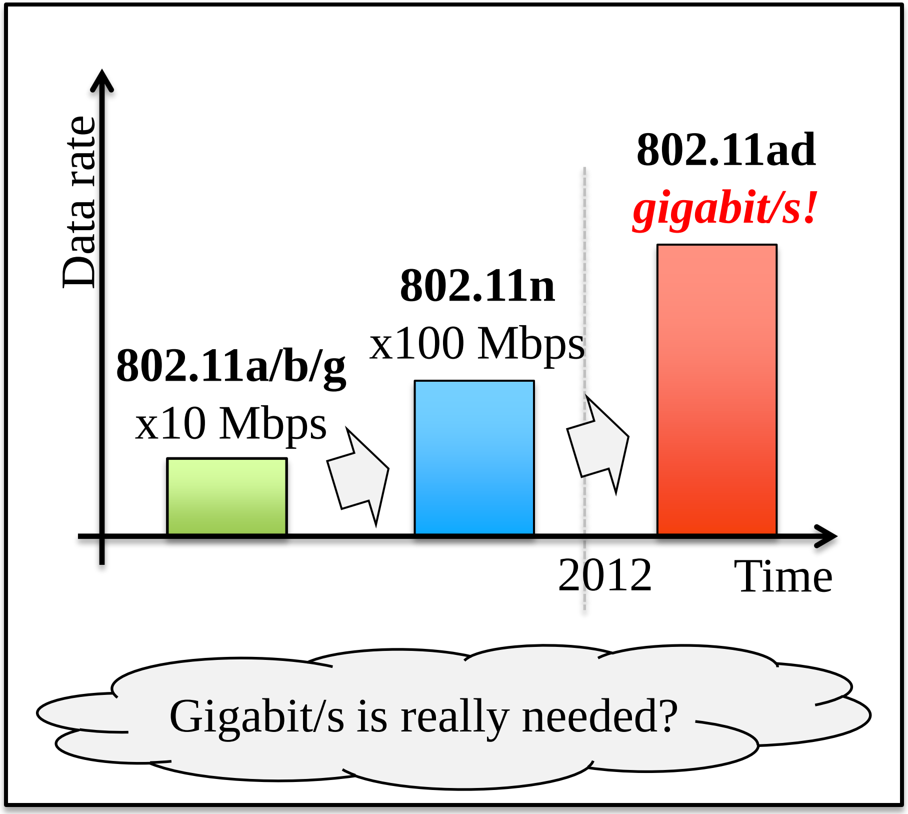
Quality-Aware Coding and Relaying for 60 GHz Real-Time Wireless Video Broadcasting

IEEE International Conference on Communications (ICC)
Budapest, Hungary, June 2013.

Presenter
Joongheon (Joon) Kim, Ph.D. Candidate of Computer Science,
University of Southern California, Los Angeles, CA, USA
Email: joongheon.kim@usc.edu

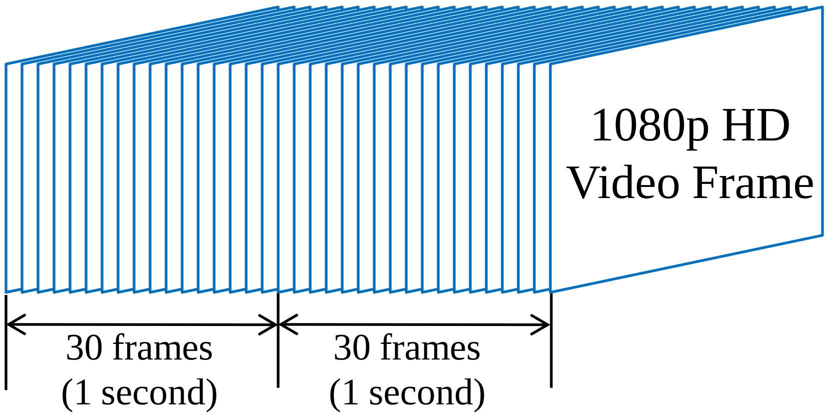
Introduction – Next Generation *Wireless*

Evolution



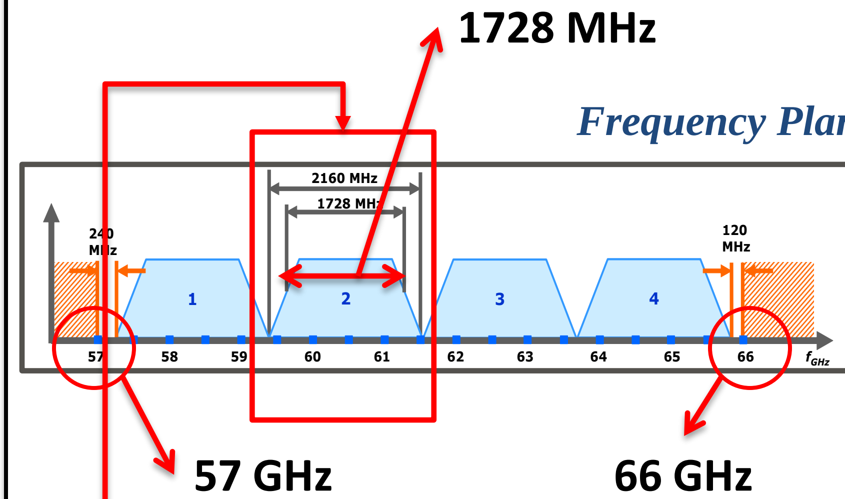
Introduction – Next Generation *Wireless*: Motivation

Uncompressed 1080p HD Video Streaming



To transmit 30 "1080p HD video frames" in one second (standard mode),
around 1.5 gigabit/s
data rates are required.

How mm-wave can support gigabit/s?



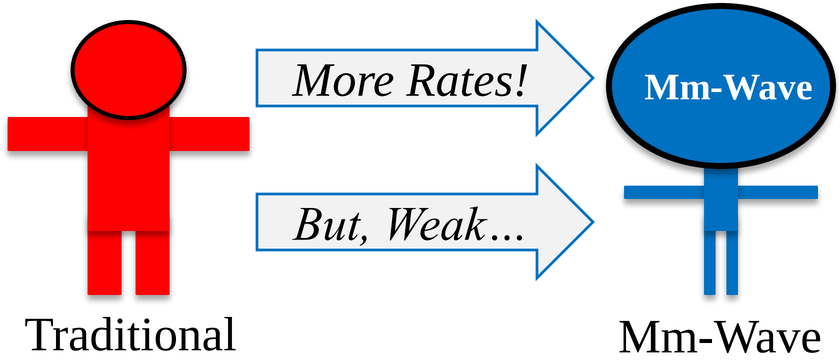
Research Challenges and Solution Approaches

Friis Path Loss Model:

$$\boxed{P_{RX}} = \frac{G_{TX} G_{RX} c^2}{(4\pi d)^2 \boxed{f_c^{\,2}}} P_{TX}$$

12^2 times weaker than 5 GHz signals

$(60G/5G)^2 = 12^2$ times higher than 5 GHz signals



Solution 1

Work Together!

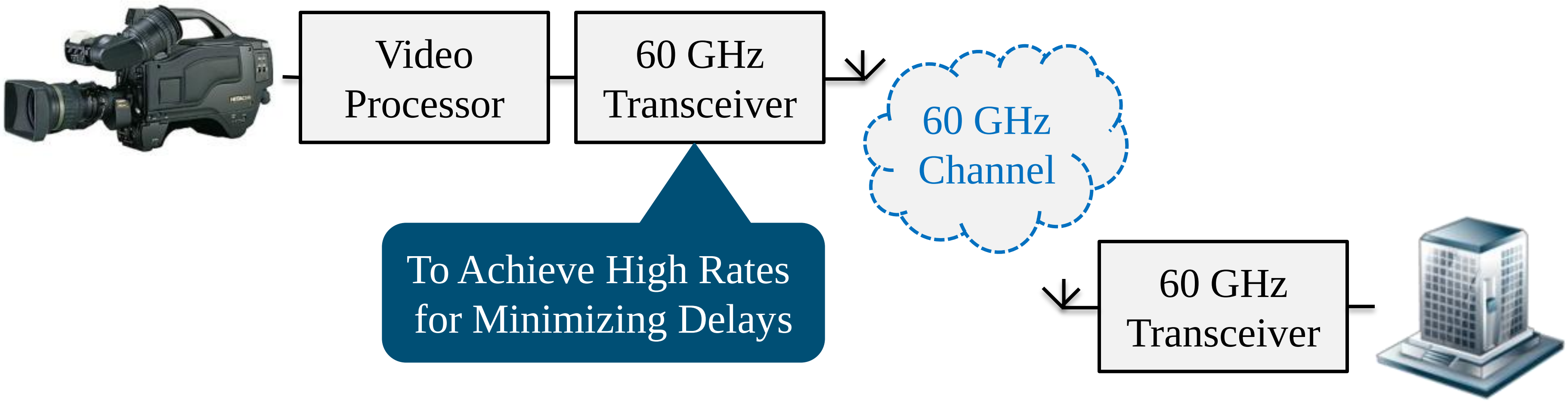
Relaying

Solution 2

Concentrate the signal!

Beamforming and Training

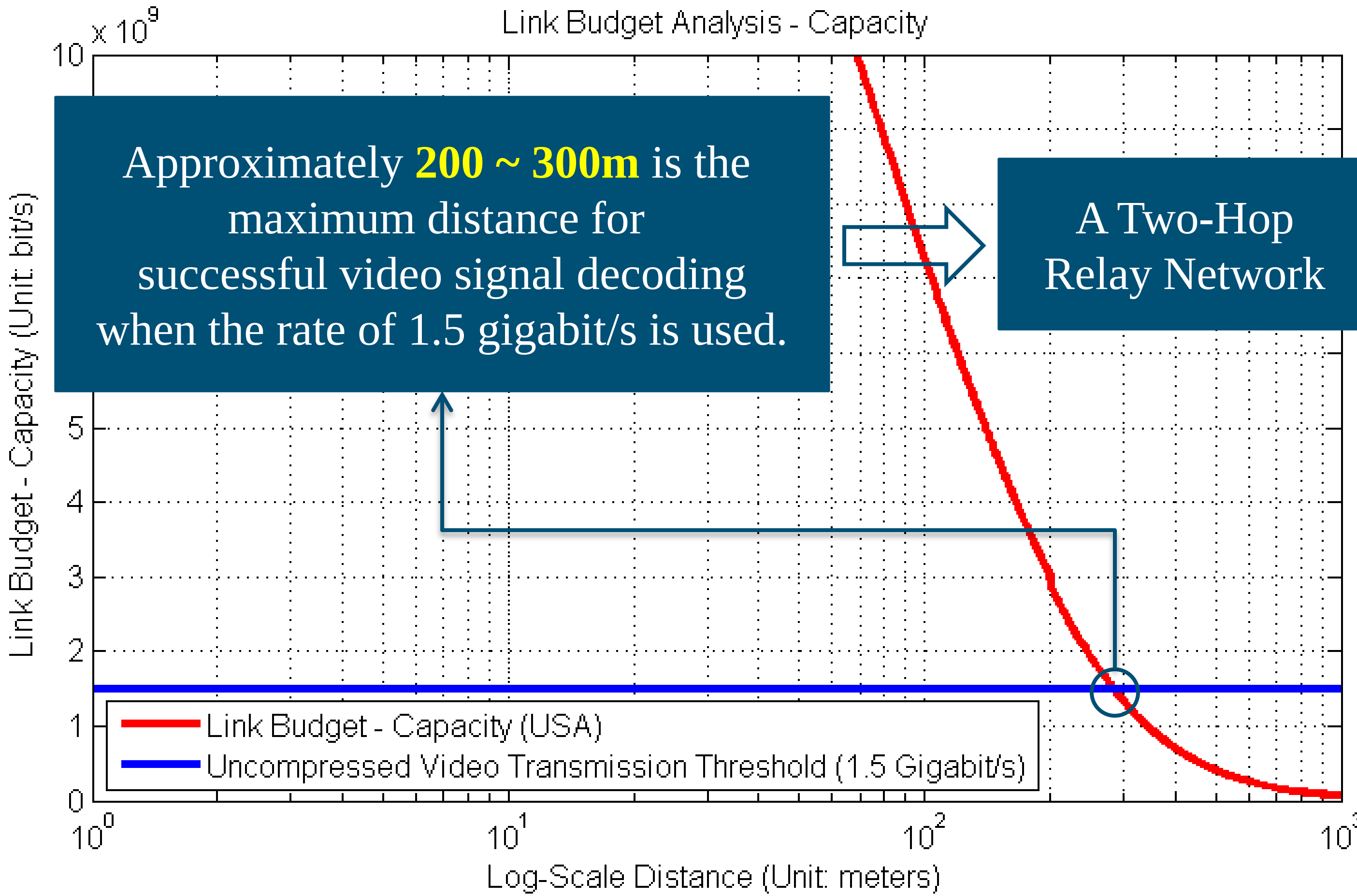
Application Scenario



Our Objective

How can we **maximize the sum quality of delivered video streams** from wireless cameras to a broadcasting center?

Link Budget Analysis



Approximately **200 ~ 300m** is the maximum distance for successful video signal decoding when the rate of 1.5 gigabit/s is used.

A Two-Hop Relay Network

Related Work

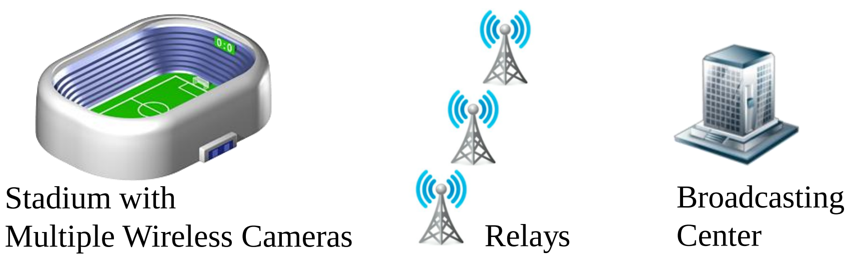
	ICME07	TWC07	CSVT09	MILCOM07	JSAC12	PIMRC11	Proposed
Route Selection	O	O	O	O	O	O	O
Rate Allocation	X	X	X	X	O	O	O
Millimeter-Wave Channels	X	X	X	X	X	O	O
Multiple-Antenna Elements	X	X	X	X	X	X	O
Video Streaming	O	O	O	O	X	O	O
Limited Number of Relays	-	-	-	-	-	X	O

- **[ICME07]** M.-H. Lu, P. Steenkiste, T. Chen (**Carnegie Mellon**)
- **[TWC07]** S. Mao, X. Xheng, Y.T. Hou, H.D. Sherali, J.H.Reed (**Virginia Tech**)
- **[CSVT09]** W. Wei, A. Zakhor (**UC-Berkeley**)
- **[MILCOM07]** S. Murthy, P. Hegde, V. Parameswaran, B. Li, A. Sen (**Arizona State**)
- **[JSAC12]** S. Sharma, Y. Shi, Y.T. Hou, H.D. Sherali, S. Kompella (**Virginia Tech**)
- **[PIMRC11]** J. Kim, Y. Tian, S. Mangold, A.F. Molisch (**USC**)

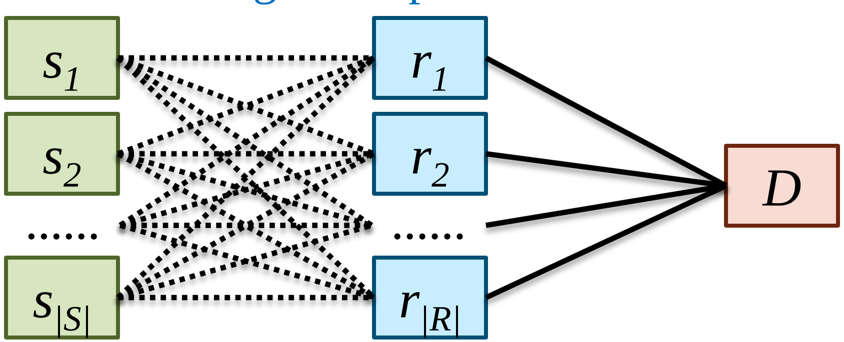
A Reference System Model

Network Model

A Brief Conceptual Model

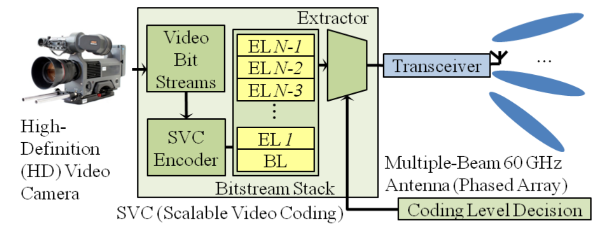


Logical Representation

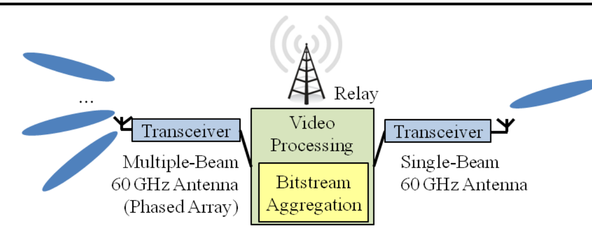


System Component Architectures

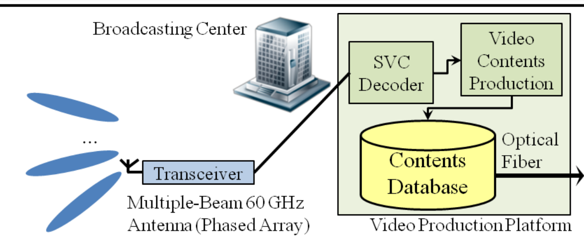
Wireless Camera Architecture



Relay Architecture



Broadcasting Center Architecture



System Specification

System Specification

The number of beams can be specified in sources and relays.

Three Possible Scenarios

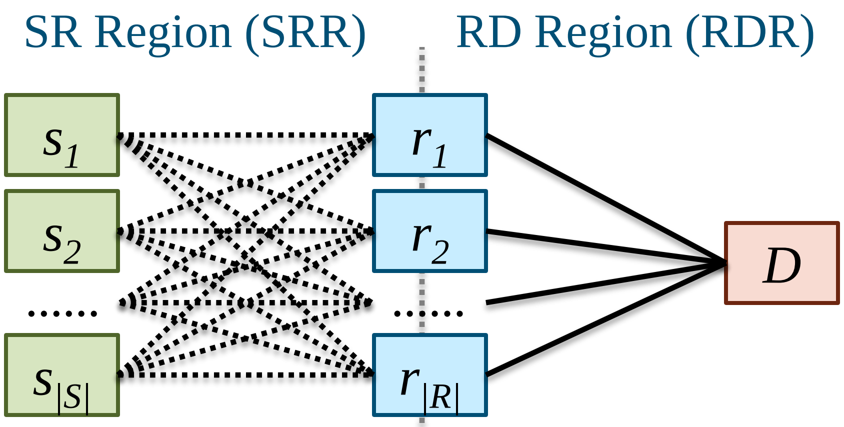
Multi-Beams at Sources and Relays

Single-Beams at Sources and Multi-Beams at Relays

Single-Beams at Sources and Relays

A Reference Network Model and Notations

Network Model and Objective



Objective:

Max the overall delivered video qualities

- Relay Selection
- Rate Selection

Notations

Notation	Description
$\mathcal{S}$	Set of sources
$\mathcal{R}$	Set of relays
D	Destination
s_i	Source i, $\forall i \in \{1, \cdots, \lvert\mathcal{S}\rvert\}$
r_j	Relay j, $\forall j \in \{1, \cdots, \lvert\mathcal{R}\rvert\}$
$\mathcal{A}^{\mathrm{SRR}}_{s_i \to r_j}$	Max achievable rate between s_i and r_j
$\mathcal{A}^{\mathrm{RDR}}_{r_j \to D}$	Max achievable rate between r_j and D
$a^{\mathrm{SRR}}_{s_i \to r_j}$	Data rate between s_i and r_j
$x^{\mathrm{SRR}}_{s_i \to r_j}$	Connectivity index between s_i and r_j
$\underline{a}^{\mathrm{SRR}}_{s_i \to r_j}$	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

Initial Formulation

Formulation

$$\max : \sum_{i=1}^{|\mathcal{S}|} f_q\left(\sum_{j=1}^{|\mathcal{R}|} \frac{1}{2} a^{\text{SRR}}_{s_i\to r_j} x^{\text{SRR}}_{s_i\to r_j}\right)$$

Subject To

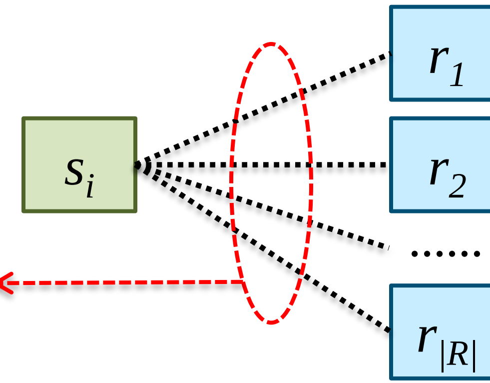
$$\begin{aligned}
\sum_{i=1}^{|\mathcal{S}|} a^{\text{SRR}}_{s_i\to r_j} x^{\text{SRR}}_{s_i\to r_j} &\le \mathcal{A}^{\text{RDR}}_{r_j\to D}, \forall j\\
\sum_{i=1}^{|\mathcal{S}|} x^{\text{SRR}}_{s_i\to r_j} &\le B_{r_j}, \forall j\\
\sum_{j=1}^{|\mathcal{R}|} x^{\text{SRR}}_{s_i\to r_j} &\le B_{s_i}, \forall i\\
\underline{a}_{s_i} &\le \sum_{j=1}^{|\mathcal{R}|} a^{\text{SRR}}_{s_i\to r_j} x^{\text{SRR}}_{s_i\to r_j}, \forall i,\\
a^{\text{SRR}}_{s_i\to r_j} &\le \mathcal{A}^{\text{SRR}}_{s_i\to r_j}, \forall i, \forall j,\\
x^{\text{SRR}}_{s_i\to r_j} &\in \{0,1\}, \forall i, \forall j,
\end{aligned}$$

Variables and Quality Bounds

Quality Bounds

Each camera has
a quality lower bound.

Should be larger than
its low bounds.



Data rate between source *i* and relay *j* (positive)

Path selection between source *i* and relay *j*
(Boolean: 0 or 1)

Initial Formulation

Formulation

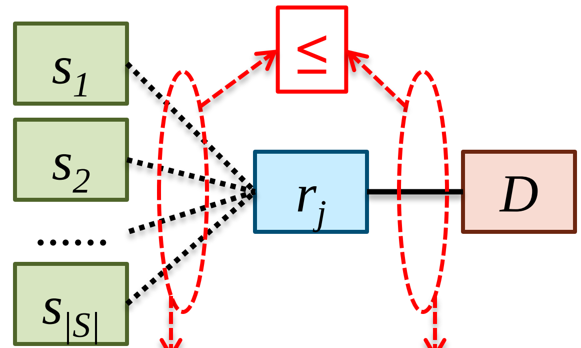
$$\max : \sum_{i=1}^{|\mathcal{S}|} f_q\left(\sum_{j=1}^{|\mathcal{R}|} \frac{1}{2} a^{\mathrm{SRR}}_{s_i\to r_j} x^{\mathrm{SRR}}_{s_i\to r_j}\right)$$

Subject To

$$\begin{aligned}
\sum_{i=1}^{|\mathcal{S}|} a^{\mathrm{SRR}}_{s_i\to r_j} x^{\mathrm{SRR}}_{s_i\to r_j} &\leq \mathcal{A}^{\mathrm{RDR}}_{r_j\to D}, \forall j \\
\sum_{i=1}^{|\mathcal{S}|} x^{\mathrm{SRR}}_{s_i\to r_j} &\leq B_{r_j}, \forall j \\
\sum_{j=1}^{|\mathcal{R}|} x^{\mathrm{SRR}}_{s_i\to r_j} &\leq B_{s_i}, \forall i \\
a_{s_i} &\leq \sum_{j=1}^{|\mathcal{R}|} a^{\mathrm{SRR}}_{s_i\to r_j} x^{\mathrm{SRR}}_{s_i\to r_j}, \forall i, \\
a^{\mathrm{SRR}}_{s_i\to r_j} &\leq \mathcal{A}^{\mathrm{SRR}}_{s_i\to r_j}, \forall i, \forall j, \\
x^{\mathrm{SRR}}_{s_i\to r_j} &\in \{0,1\}, \forall i, \forall j,
\end{aligned}$$

Constraints: Relay Capacity and Selection

Relay Capacity



Sum of all incoming rates

Link Capacity

Relays: (# of incoming streams) ≤ (# of beams)

Sources: (# of outgoing streams) ≤ (# of beams)

Initial Formulation

Formulation

$$\max : \sum_{i=1}^{|\mathcal{S}|} f_q \left(\sum_{j=1}^{|\mathcal{R}|} \frac{1}{2} a_{s_i \to r_j}^{\mathrm{SRR}} x_{s_i \to r_j}^{\mathrm{SRR}} \right)$$

Subject To

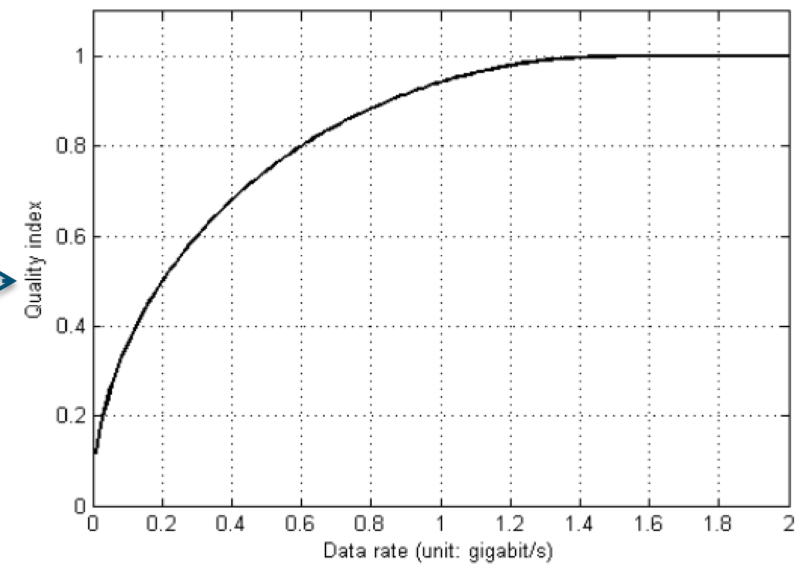
- In the paper, per-link quality is considered instead of per-source quality consideration.
- Considering per-link quality is valid when (i) sources have single-beam antennas or (ii) multiple streams emanate from one source location, each being transmitted via one link.
- In other situations, Considering the quality of each source is the most meaningful consideration.

Object Function: Delivered Quality Maximization

Maximizing the *sum qualities*

- f_q: a function of quality for the given rates

Quality Function based on PSNR



Formulation Simplification: Concept

Formulation

$$\max : \sum_{i=1}^{|\mathcal{S}|} f_q\left(\sum_{j=1}^{|\mathcal{R}|} \frac{1}{2} a^{\text{SRR}}_{s_i \to r_j} x^{\text{SRR}}_{s_i \to r_j}\right)$$

Subject To

$$\begin{aligned}
\sum_{i=1}^{|\mathcal{S}|} a^{\text{SRR}}_{s_i \to r_j} x^{\text{SRR}}_{s_i \to r_j} &\leq \mathcal{A}^{\text{RDR}}_{r_j \to D}, \forall j \\
\sum_{i=1}^{|\mathcal{S}|} x^{\text{SRR}}_{s_i \to r_j} &\leq B_{r_j}, \forall j \\
\sum_{j=1}^{|\mathcal{R}|} x^{\text{SRR}}_{s_i \to r_j} &\leq B_{s_i}, \forall i \\
\underline{a}_{s_i} &\leq \sum_{j=1}^{|\mathcal{R}|} a^{\text{SRR}}_{s_i \to r_j} x^{\text{SRR}}_{s_i \to r_j}, \forall i, \\
a^{\text{SRR}}_{s_i \to r_j} &\leq \mathcal{A}^{\text{SRR}}_{s_i \to r_j}, \forall i, \forall j, \\
x^{\text{SRR}}_{s_i \to r_j} &\in \{0, 1\}, \forall i, \forall j,
\end{aligned}$$

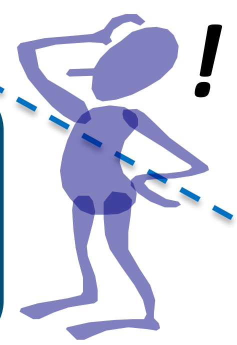
$$a^{\text{SRR}}_{s_i \to r_j} \leq \mathcal{A}^{\text{SRR}}_{s_i \to r_j}, \forall i, \forall j$$

$$\Downarrow$$

$$a^{SRR}_{s_i \to r_j} \leq \mathcal{A}^{SRR}_{s_i \to r_j} \cdot \boxed{x^{SRR}_{s_i \to r_j}}, \forall i, \forall j$$

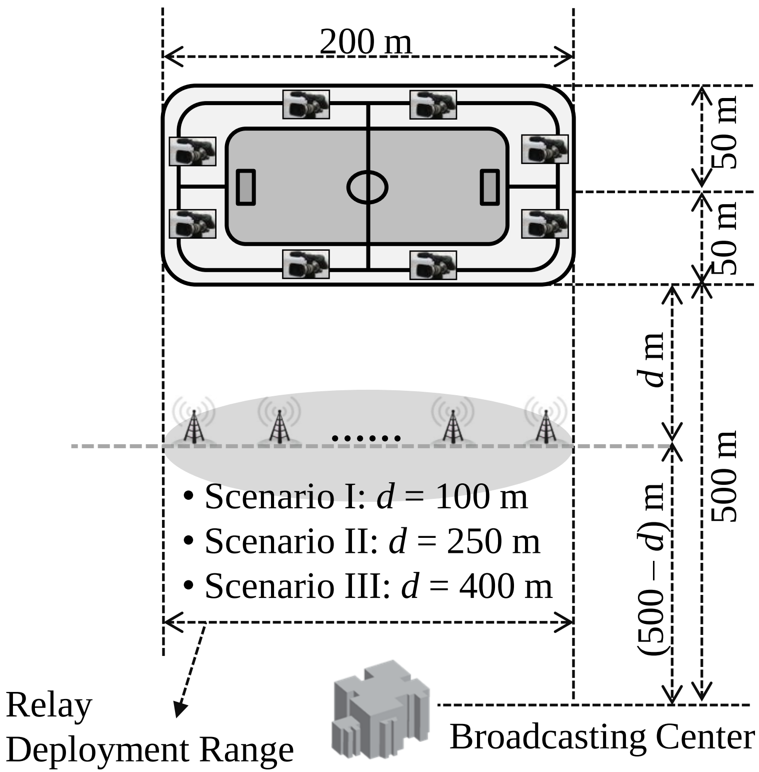
s_i

r_j



If this link (i.e., x) is disconnected (i.e., x=0), the corresponding data rate (i.e., a) should be zero.

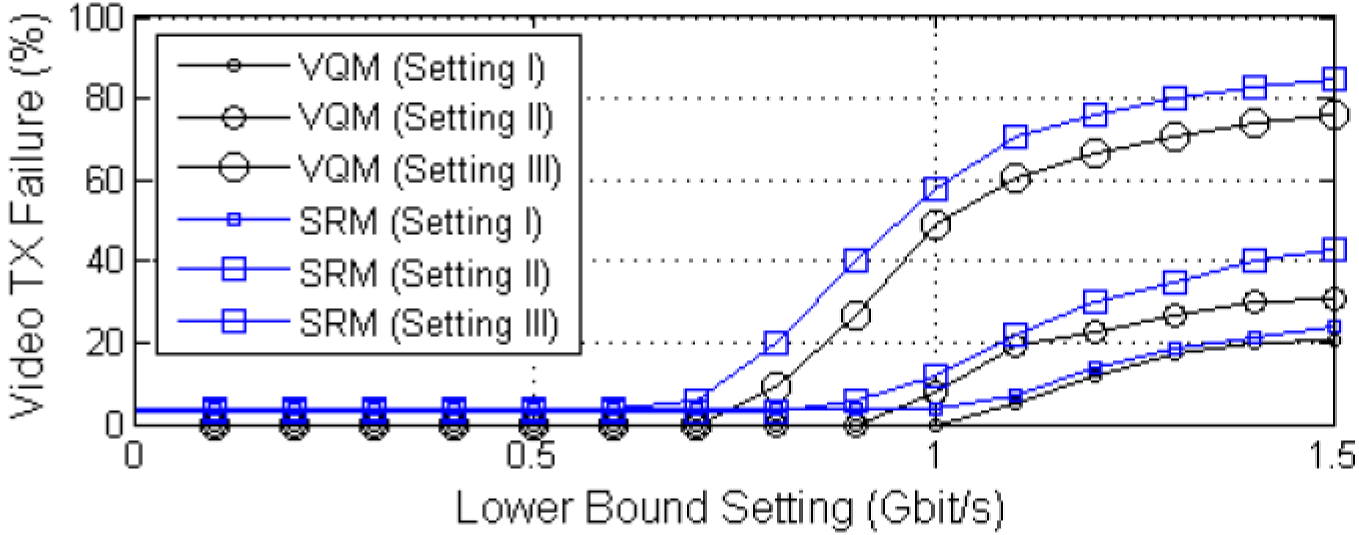
Performance Evaluation – Setting



Our Scheme and Control Group

- **Proposed Scheme**
  - ***VQM*** – Video Quality Maximization
- **Control Group**
  - ***SRM***
    → Sum Rate Maximization
    → No Quality Consideration on our Objective Function
  - ***JRSR***
    → Joint Relay Selection and Routing
    → [JSAC12] in Related Work

Performance Evaluation – Impact of Lower Bounds

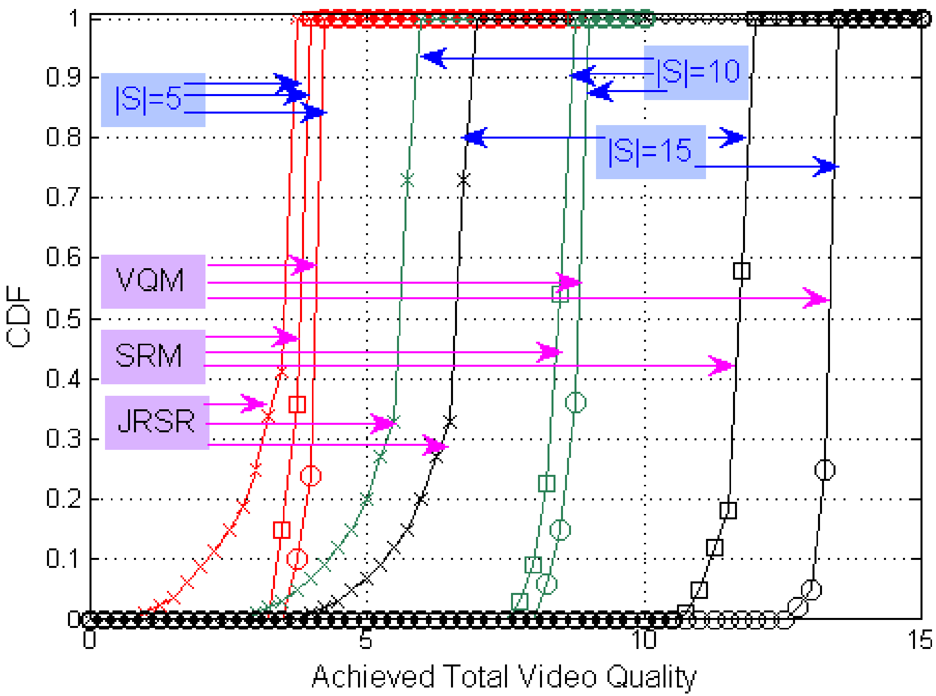


VQM has better performance than SRM for all settings

Setting III suffers significantly from the higher required per-stream quality

Performance Evaluation – CDF of Aggregated Video Quality

Setting I



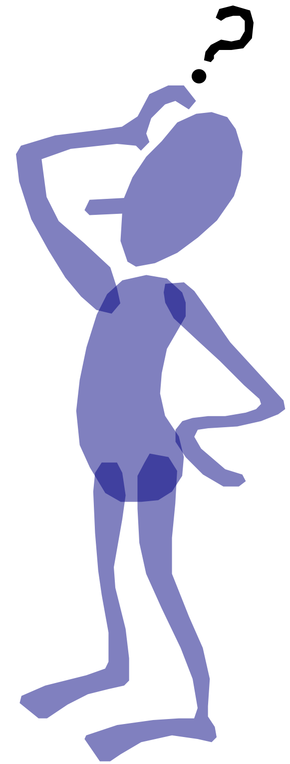
The performance of JRSR is worse than that of both SRM and VQM

VQM always has the highest performance than SRM and JRSR in terms of the achieved total video quality distribution

Concluding Remarks – Quality-Aware SVC and Relaying

Issues	Solutions
Relays for Mm-Wave	Relay Network Construction via Link Budget Analysis
Video Quality Consideration	Sum Quality Consideration Formulation
Computation	Formulation Simplification

Q&A



Appendix

- A) Assumptions
- B) Link Budget Analysis
- C) Solving the Convex or Non-Convex Programming

Appendix A: Assumptions and System Specification

Assumption: Interference

Due to the high-directionality of
mm-wave beams (1º~15º),
the interferences are not considered.

Example

Short range version with 1ft. Antenna

Features

- Frequency band
  57~64GHz(59~66GHz for JAPAN)
- Full-duplex Gigabit Ethernet - 1.25 Gbps
- Highly secure, "pencil-beam" antennas - less than 1.2 deg.
- Interference free operation.
- High density deployment without co-location problems
- Extremely low latency -measured in nanoseconds
- All-in-one outdoor, compact design - no IDU required.
- Extreme reliability - up to 99.999%
- IP66 Outdoor Rate Enclosure
- Easy antenna alignment using voltmeter RSSI test points.

Appendix B: Link Budget Analysis

Link Budget Analysis

$$C = B \cdot \log_2 (1 + \boxed{\mathrm{SNR}})$$

$$\mathrm{SNR} = P_{signal} / P_{noise}$$ (a linear scale)

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

- E: EIRP (40 dBm, USA)
- G_r: Receiver Antenna Gain (40 dB): 60 GHz Outdoor Scalar Horn Antennas
- W: Shadowing margin (10dB)
- Oxygen Attenuation: $O(d) = \frac{15}{1000} d$
  - If $d < 200$m, $O(d) = 0$
- Path Loss: $F(d) = 10 \log_{10} \left(\frac{\lambda}{4\pi d} \right)^n$
  - n: path loss coefficient (2.5)
  - d: distance
  - λ: wavelength (5mm)

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

- $k_B T_e$: Noise Power Spectral Density (-174 dBm/Hz)
- B: Bandwidth (2.16 GHz)
- F_N: Noise Feature (6dB)

Appendix C: Solving Optimization

Solving the Convex or Non-Convex Programming

Convex?

Multiplied
two independent
variables (*a* and *x*)

Non-Convex
MINLP

Convex?

No

Non-Convex

Cannot guarantee the optimal solutions

- Heuristics
- Linear Approximation

Relaxation
$0 \leq x \leq 1$

Linear Approximation
(SOS Approximation)

Branch-and-Bound, Branch-and-Cut, …

Yes

Solving MILP

(BBLP: Branch-and-Bound with Linear Programming)

- Step #1: Relaxation to Linear Programming Form
- Step #2: Find Optimal Solutions
- Step #3: Find the Integer Solutions (using BBLP)