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Multi-Input– Multi-Output Network Systems in DERS using Self-Tuning Proportional Integrative plus Derivative (SPID) Controller

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.Abstract :With the ever-increasing wireless/wired data applications recently, considerable efforts have focused on the design of distributed explicit rate flow control schemes for multi-input multi- output service. This paper describes two novels wireless/wired multipoint-to-multipoint multicast flow control schemes, which are based on the distributed self-tuning proportional integrative plus derivative (SPID) controller and distributed self-tuning proportional plus integrative (SPI) controller, respectively. The control parameters can be designed to ensure the stability of the control loop in terms of source rate. The distributed explicit rate SPID and SPI controllers are located at the wireless/wired multipoint to- multipoint multicast source to regulate the transmission rate. We further analyze the theoretical aspects of the proposed algorithm, and show how the control mechanism can be used to design a controller to support wireless/wired multipoint-to-multipoint multicast transmissions. Simulation results demonstrate the efficiency of the proposed scheme in terms of system stability, fast response, low packet loss, and high scalability, and the results also show SPID scheme has better performance than SPI scheme, however, SPID scheme requires more computing time and CPU resource.

Keyword - Explicit rate, flow control, multi-input–multi output (MIMO) system, stability.

1. Introduction

The advances in multi-input–multi-output (MIMO) systems and networking technologies introduced a revolution recently, which promises significant impact in our lives. Especially with ever-increasing multicast data applications, wireless and wired multicast (multipoint-to-multipoint) transmission has considerable effect on many applications such as teleconferencing and information dissemination services. Multicast improves the efficiency of multipoint data distribution from multiple senders to a set of receivers. Unfortunately, the widely used multicast transport protocols, which are layered on top of IP multicast, can cause congestion or even congestion collapse if adequate flow control is not provided. Flow control thus plays an important role in the traffic management of multicast communications. Without an adequate flow control scheme being implemented in a multicast tree, the incoming traffic to a bottleneck link might be much more than the outgoing link capacity, which could subsequently cause the buffer to overflow, and cause excessive queuing delay or even deadlock in certain nodes.

There are many flow schemes handling unicast transmissions efficiently, and they were formulated as a discrete-time feedback control problem with delays. This control-theoretic approach to explicit rate control for available bit rate (ABR) service was further analyzed and verified using a real-network test bed in the work of Kolarov and Ramamurthy. Further achievements in this regard can also be found. All these methods are efficient in rate allocation and flow control for unicast transmission. Unfortunately, multicast flow control is much more sophisticated than that of unicast, due to the complexity of multicasting mechanism.

Several multicast flow approaches have been proposed recently. One class of them adopts a simple hop-by-hop feedback mechanism, in which the feedback, i.e., backward control packets (BCPs), from downstream nodes are initially gathered at branch points, and then are transmitted upward by a single hop upon receipt of a forward control packet (FCP).This kind of manipulation can be carried out on the basis of the tree structure in a multicast transmission. The main merit of these methods lies in the simplicity of the hop-by-hop mechanism.

However, at the same time, they often lead to the so called consolidation noise problem due to incomplete feedback information. To overcome this drawback, Jain *et al.* and Lee *at al*., proposed a method, called feedback synchronization at each branch point, by accumulating feedback from all downstream branches. These schemes then introduce another problem of slow transient response due to the feedback from "long" paths. Such delayed congestion feedback can cause excessive queue buildup/packet loss at bottleneck links.

This method has studied the system dynamics by using the binary congestion feedback in the scenarios of both persistent and on–off elastic traffic services, which defines that the data transfer rate is adjusted at the source, depending on the available bandwidth at the bottleneck. A lot of approaches use queue schemes to solve congestion control problems.

Queue schemes in routers make sure that the buffer occupancy stabilizes and never overflows the buffer capacity. Our schemes are based on the explicit rate schemes in the senders. These are active and effective methods to adjust the sending rates, and reduce the packets loss. The major difficulty in designing multicast flow control protocols arises from the long and heterogeneous RTTs involved in the closed-loop control. In-depth research remains in the following three aspects. First, the existing algorithms usually lack scalability, since they require each router to keep maintaining the saturation and as virtual sessions (VSs) travel through it, this yields a major computational bottleneck. To this end, we are going to present an algorithm that is scalable. Second, the known flow control methods usually do not have explicit control over link buffer occupancy; as a consequence, the allocated rate can wander considerably before converging, and the link flow can temporarily exceed the capacity.

To attack this problem, we will focus on the stability of our rate control scheme. Third, no explicit rate (ER) allocation has been given in the known approaches. This paper will consider ER-based rate control with an ER feedback (ER value). Such an ER-based scheme is responsive to network congestion and can serve WAN environments quite well where the bandwidth-delay product is usually large.

In this paper, we develop a distributed ER allocation algorithm to overcome the vulnerability due to the heterogeneous multicast receivers. In our scheme, flow controllers regulate the source rate at a multicast tree, which accounts for the buffer occupancies of all destination nodes. The proposed control scheme uses a distributed self-tuning proportional integrative plus derivative (SPID) controller or uses a distributed self-tuning proportional plus integrative (SPI) controller. The control parameters can be designed to ensure the stability of the control loop in terms of source rate. We further show how the control mechanism can be used to design a controller to support multipoint-to-multipoint multicast transmission based on ER feedback. System stability criterion is derived in the presence of destination nodes with heterogeneous RTTs. We analyze the theoretical aspects of the proposed algorithm and verify its agreement with the simulations

in the case of a bottleneck link appearing in a multicast tree. Simulation results demonstrate the efficiency of the proposed scheme in terms of system stability and fast response to the buffer occupancy, as well as controlled sending rates, low packet loss, and high scalability. Furthermore, the results also show that SPID scheme has better performance than SPI scheme, though the SPID scheme requires more computing time and CPU resources.

2. Network Configuration Model

In each multicast connection and every sampling period, the multicast source issues and transmits a FCP to the downstream nodes (the branch node and destination nodes), and a BCP is constructed by each downstream node and sent back to the source. After the multicast source receives the BCPs from the downstream nodes, it will take appropriate action to adjust its transmitting rates of multicast traffic based on the computed value of the SPID controller. After receiving the data packets coming from the branch point, the receivers construct BCPs and send them back to the branch point.

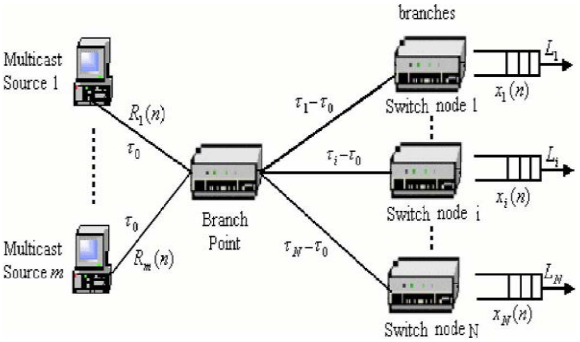

Fig.1. Multicast configuration of multiple points to multiple points.

The considered multicast service is described as follows. The number of packets sent out by the switch node i in one interval T is denoted by Li [21], the switch node i has the forward delay τi $(1 \le i \le N)$ from sources, and $\tau 0$ is the delay from sources to the neighboring downstream node. Then, the round-trip delay (RTD) for the switch node i is $\tau R = 2\tau i$ and $\tau = \max\{\tau R1, \tau R2, \dots, \tau RN\}$. We further assume that τi and τRi are integers, which is reasonable by adjusting T. And the link delay is dominant compared to the other delays, such as proceeding delay, queuing delay, etc. In the model, we assume that $\tau i \le \tau j$ when $1 \le i \le j \le N$. Each branch point schedules the packets in a first-come first-served way. The component $Ri(n)$ represents the receiving rate of the computed receivers i at time slot n.

The buffer occupancy of the switch node i is determined by

$xi(n+1) = \mathrm{Sat}Ki\{xi(n)+\sum eqRq(n-\tau i)-Li\}$ – (1)

where Ki is the buffer size, $xi(n)$ is the buffer occupancy of the switch node i at time slot n, and $Rq\,(n-\tau i)$ is the sending rate of the qth $(1 \le q \le m)$ source to the switch node $i (1 \le i \le N)$,

with $\mathrm{Sat}Ki\,\{xi\} = \left\{ \begin{array}{l} Ki,\ xi > Ki \\ xi\ ,\ 0 \le xi \le Ki \\ 0,\ xi < 0 \end{array} \right\}$

and

$eq = \left\{ \begin{array}{l} 1, \text{ if the } q\text{th source is active} \\ 0, \text{ if the } q\text{th source is not active} \end{array} \right\}$

After lifting the saturation restriction, (1) can be written as

$xi(n+1) = xi(n) + \sum eqRq\,(n-\tau i) - Li$ - (2)

3. SPID and SPI Schemes

The router buffer occupancy is expected to stabilize in the neighborhood of the desired level. If $x(n)$ is too high, it often leads to buffer overflow and packet loss. In addition, under this circumstance, long queuing delay usually results in time out and retransmission, which, in turn, builds up the mounting buffer occupancy; consequently, a vicious cycle is formed. If $x(n)$ is too low, it increases the likelihood of link under utilization during occasionally idle periods. Thus, the router buffer occupancy plays an important role in the congestion control that is chosen to be the feedback carried in BCP.

A. SPID and SPI Algorithms

Generally, among all downstream nodes, the most congested one, defined as the worst node, deserves special attention. On the basis of this consideration, we propose the following SPID control scheme:

$Rq\ (n) = \mu + a\sum(xi(n - \tau i) - xi) + \sum bjRq(n - j) + c\sum(xk\ (n - \tau k\ ) - xk\ (n - \tau k - 1)$ - (3)

where a, bj ($j = 1, 2, \ldots, \tau$), and c are the proportional, integral, and derivative control gains, respectively, which are to be determined by the stability criteria. These coefficients are used to locate all the poles of the closed-loop equations (2) and (3) within the unit circle to ensure stability. The component ッxi is the target queue length and μ is the maximum sending rate of sources.

To save computing time and CPU resources, here we present a simple SPI control scheme as follows:

$Rq\ (n) = \mu + a\sum(xi(n - \tau i) - xi) + \sum bjRq\ (n - j)$ - (4)

where a and bj ($j = 1, 2, \ldots, \tau$) are the proportional and integral control gains, respectively, which are to be determined from the stability criteria based on control theory. Similarly, these coefficients should make all the poles of the closed-loop equations (2) and (4) within the unit circle to ensure stability.

In (3) and (4), if the buffer occupancy of the switch node i is measured at the instances $n - \tau i$, after the feedback delay τi, the BCP reaches the controller located at the source q ($q = 1, 2, \ldots, m$), and the source then takes out the buffer occupancy of the destination nodes at time slot $t = n$. By doing so, the proposed controller can be expected to have flexibility to cope with the sharp oscillation in buffer occupancy that could cause the network to lose packets. In addition, the calculation in (3) and (4) is completely independent of virtual connections traveling through the multicast session. This means the scheme has scalability.

B. Implementation of the SPID and SPI Algorithms

Each branch point of the multicast tree replicates each data packet and FCP from its upstream node to all its downstream branches. The downstream nodes return their congestion information via BCPs to the parents through the backward direction once they receive FCPs. Moreover; the branch nodes consolidate the BCPs that carry all the available rates and the relevant link band width from different branches into one BCP and feedback the new BCP to their upstream node. Associated rate adaptors are located at multicast sources.

There is a single first-in first-out (FIFO) queue to multiplex all flows traveling through the outgoing link. Assume that congestion never happens at the router connected with the sources; hence, these two can be consolidated into one node, which is true in most cases in real networks.

Before we present the algorithm, we specify the following variables. The variablemulticasttree[i] = 1(0) means the ith branch point receives (does not receive) FCP or BCP control packet, while receiver tree[j] = 1(0) means the jth branch point receives (does not receive) confirmations from all destination nodes.

4. System stability analysis

The ability of a multicast tree to provide efficient heterogeneous distributed communication that can guarantee multiple qualities of service can only be realized by effective traffic management schemes. In this paper, a rate-based scheme is used rather than a window-based adaptation algorithm to achieve congestion control in multi rate–multicast control (MR-MCC) tree. The window-based scheme has extra complexity in maintaining and synchronizing the congestion window across all receivers, and it usually generates data bursts periodically. In our proposed SPID and SPI control schemes, the rate adaptation takes into account the buffer occupancies of the destination nodes as well as the variation of RTTs. The controller parameters are designed to guarantee the stability of rate, which ensures a smooth dynamic rate adaptation to minimize packet loss rate. This, in turn, brings an obvious advantage of the proposed scheme over the widely adopted additive increase and multiplicative decrease.

A. SPID System Stability Analysis

Considering(2),ifz transformation is applied, one can easily arrive at

$$(z-1)\ Xi(z)=\sum eqRq\ (z)\ z^{-\tau i} - LiD(z) \quad (5)$$

where the z transformation of $xi(n)$ and $Rj\ (n)$ are, respectively, described by $Xi(z)\ =\sum\ xi(n)\ z^{-n}$, $Rq\ (z) = \sum Rq\ (n) z^{-n}$, and $D(z)\ = z^{-n} = z/z-1$.

Taking the z transform of (3), it yields

$$Rq\ (z) = \mu D(z) + a\sum[z^{-\tau i}Xi(z) - xiD(z)] +\_\tau j$$

$$= \sum bj\, z^{-j}Rq\ (z) + c\sum\ (z^{-\tau i} Xi(z) - z^{-\tau i\ -1}Xi(z))$$

- (6)

From (5) and (6), one has

$$\Delta 1\ (z) Rq\ (z)\ = \sum(-LiD(z) z^{-\tau Ri/2} - xiD(z) (z - 1)) - c\sum z^{-\tau R\, i/2}\ LiD(z) (1 - z^{-1}) + \mu D(z) (z - 1) \quad - (7)$$

where we denote

$$\Delta 1\ (z) = (1 - \sum bj\, z^{-j})\ (z-1)\ - a\sum z^{-\tau R\, i} - c\sum\ (z^{-\tau R} k - z^{-\tau R\, k\, -1})\ - (8)$$

The coefficients a, $bj\ (j = 1, 2, \ldots, \tau)$, and c are determined by the stability criteria of the control theory.

we use Schur–Cohn stability test here. Generally, for a polynomial

$$A_Q\ (z) = 1+\sum a^{(Q)}\ n\, z^{-n} \qquad - (9)$$

Algorithm 1: Schur–Cohn stability test

Step 1) Start with the original polynomial of degree Q (Q coefficients).

Step 2) Generate a sequence of polynomials recursively.

$Ai(z)$, $i = Q : -1 : 0$, according to

$$A_{i-1}\ (z) = (Ai(z) - q_i z^{-i} Ai(z^{-1}))/(1 - q^{2i}) \quad - (10)$$

where $qi = a_{(i)} i$. Note that $z^{-i}Ai(z^{-1})$ is a flipped version of $Ai(z)$.

Step 3) The zeros of the polynomial $A_Q\ (z)$ are inside the unit circle iff

$$/qi\ / < 1,\ i = Q : -1 : 1 \qquad - (11)$$

With regard to CP (8), some manipulations are needed for it to satisfy the form of the polynomial $AQ(z)$. This is done in the following manner:

$\Delta 1\ (z) = z[1 - (1 + b1)z^{-1} + (b1 - b2)z^{-2}$

$+\ldots. + (b_{\tau-1} - b_{\tau})z^{-\tau} + (b_{\tau} - a - c)z^{-\tau-1} + cz^{-\tau-2}$

$]$ − (12)

We have

$\Delta_1\ (z) = z\Delta_1\ (z).$

Without loss of generality, we group these nodes into one class, with a small variation of time delays and sending rates. Thus, we divide N destination nodes into M groups based on the RTTs, and in each group, the RTT is assumed to be equal,

i.e.,

$\{\tau R1, \tau R2, \tau R3, \ldots, \tau RN\} = \{\tau 1, \ldots \tau 1, \tau 2, \ldots \tau 2, \ldots, \tau M, \ldots, \tau M\}$ − (13)

the CP (12) is

$\Delta_1\ (z) = z[1 - (b1 + 1)z^{-1} + \cdot\ \cdot\ \cdot + (b_{\tau R\,1-1} - b_{\tau R\,1}) + (b_{\tau R\,1} - b_{\tau(R\,1)+1} - an_1 - cn_1)z^{-(\tau R\,1-1)} + (b_{(\tau R\,1+1)}$

$- b_{(\tau R\,1)+2} + cn_1)z^{-(\tau R\,1-2)} + (b_{(\tau R\,n\,i-1)} - b_{\tau R\,n\,i})z^{-\tau R\,n\,i}\ .$

$..+ (b^{\tau R\,n\,i} - b^{\tau(R\,n\,i)+1} - ani - cn_i)z^{-\tau R\,n\,i-1} + (b^{\tau(R\,n\,i)+1}$

$- b^{\tau(R\,n\,i)+2} + cn^i)z^{-\tau(R\,n\,i)-2} + \cdot\ \cdot + (b\tau - 1 - b\tau$

$)z^{-\tau} + (b^{\tau - anM - cnm)}$

$z-\tau-1 + cnM\ z-\tau-2\ ]$ - (14)

Let

$b1 + 1 = \varepsilon$

$b2 - b1 = \varepsilon$

$b3 - b2 = \varepsilon$

$\ldots$

$b\tau^{R\,1} - b^{\tau R\,1-1} = \varepsilon$

$an_1 + b\tau^{R\,1+1} + cn_1 - b\tau^{R\,1} = \varepsilon$

$b\tau^{R\,1+2} - cn_1 - b\tau^{R\,1+1} = \varepsilon$

$\ldots$ -(15)

$b\tau^{R\,n\,i} - b^{(\tau R\,n\,i-1)} = \varepsilon$

$b^{(\tau R\,n\,i+1)} - b\tau^{R\,n\,i} + an_i + cn_i = \varepsilon$

$b\tau^{R\,n\,i+2} - b\tau^{R\,n\,i+1} - cn_i = \varepsilon$

$\ldots$

$b^{\tau} - b^{\tau-1} = \varepsilon$

where $i = 1, 2, 3, \ldots, (M - 1)$, and

$an_M + cn_{M - b\tau} = \varepsilon$ - (16)

$-cn_M = \varepsilon$ -(17)

Then we can obtain

$a = (\tau\varepsilon + 2\varepsilon - 1)/N$ -(18)

$c = (-\varepsilon)/n_M$ -(19)

and

$bj = j\varepsilon - 1;\ (j = 1, 2, 3, \ldots, \tau_{R1})$

$j\varepsilon - 1 - a(n_1 + n_2 + \ldots + ni) - cni\ ;$

$(j = \tau^{(Rni)} + 1)$

$j\varepsilon - 1 - a(n_1 + n_2 + \ldots + n_i);$

$(j = \tau_{Rni+2})$

$j\varepsilon - 1 - a(n_1 + n_2 + \ldots + n_i);$

$(j \in (\tau^{R1+1}, \tau];$

and $j = \tau^{Rni+3}, \ldots, \tau^{Rn(i+1)})$ -(20)

where $i = 1, 2, \ldots, (M - 1)$.

We can set

$\Delta_1\ (z) = z^{-\tau R\,j}\,[z^{(\tau R\,j+1)}, \ldots, -\varepsilon(z^{\tau R\,j} + z^{(\tau R\,j-1)} + z^{(\tau R\,j-2)}$

$+ \ldots + z + 1)]$ -(21)

From [24], when _ < 1/(τ + 2), all the zeros of (21) lie withinthe unit disc, and the original network system (2) with the controller(3) is stable.

B. SPI System Stability Analysis

On the basis of the aforementioned SPID stability analysis,we use a similar method to analyze SPI system stability.In order to analyze the stability, first we consider (4); if ztransformation is applied, one easily arrives at

$Rq(z)=\mu D(z)+a\sum[z^{-\tau i}Xi(z)\text{-}xiD(z)]+\sum bj\ z^{-jRq\,(z)}$

- (22)

From (5) and (22), one has

$\Delta_2(z)Rq\ (z) = a\sum(-LiD(z)z^{-\tau R\ i\ /2} - xiD(z)(z - 1)) + \mu D(z)(z - 1)$ -(23)

where we denote

$\Delta 2\ (z) =\big(1 - \sum bj\ z - j\big)(z - 1) - a$

$\sum z^{-\tau R\ i}$ -(24)

The coefficients a and bj ($j = 1, 2, \ldots, \tau$) are determined bythe stability criteria of the control theory. The component

$\Delta 2(z)$ is the CP of the multicast system given by (2) and (4) for SPI control system.

Based on (13), the CP (24) is

$$\Delta_2\ (z) = -z^{-\tau}\ [-z^{\tau\ +1} + (b1 + 1)z^{\tau} + (b2 - b1\ )z^{\tau\ -1}+ (b3 - b2)z^{\tau\ -2} + \ldots +(b_{\tau R\ 1}- b(_{\tau R\ 1\ )-1})z^{\tau\ -(\tau R\ 1\ )+1}+ (b(_{\tau R\ 1})+1 - b\tau R\ 1- an1\ )z^{(\tau\ -\tau R\ 1\ )}+ (b_{(\tau R\ 1\ +2)} - b^{(\tau R\ 1\ )}+1\ )z^{\tau\ -(\tau R\ 1\ )-1} + \ldots+ (b^{\tau R\ i}- b^{(\tau R\ i\ )}-1\ )z^{\tau\ -(\tau R\ i\ )}+1+ (b\tau_{\ (Ri\ +1)} - b_{(\tau R\ \ i\ \ )} - _{ani})z^{\tau\ \ -(\tau R\ \ i\ \ )} + \ldots+ (b\tau^{R(M-1)} -b(\tau^{R(M-1))-1}-an_{(M-1)})z_{\tau\ -(\tau R\ (M-1))}+ \ldots+ (b\tau - b\tau -1)z + (b\tau - an_{M}\ ]$$ -(25)

Let

$b1 + 1 = \varepsilon$

$b2 - b1 = \varepsilon$

$b3 - b2 = \varepsilon$

. . .

$b_{\tau 1}- b_{(\tau 1\ )-1} = \varepsilon$

$b_{(\tau 1\ )+1} - b_{(\tau 1\ )} - an_1 = \varepsilon$

$b_{(\tau 1\ )+2} - b_{(\tau 1\ )+1} = \varepsilon$

. . . *-(26)*

$b_{(\tau R\ i\ )} - b_{(\tau R\ i\ )-1} = \varepsilon$

$b_{(\tau R\ i\ )+1} - b_{(\tau R\ i\ )} - an_i = \varepsilon$

. . .

$b(\tau_{R\ (M\ -1))} - b(\tau_{R\ (M\ -1))}-1 - an_{(M-1)} = \varepsilon$

. . .

$b_{\tau} - b_{(\tau\ -1)} = \varepsilon$

and

$b\tau = anM$ -(27)

We obtain

$a = (\tau\varepsilon - 1)/N$ -(28)

and

$bj =j\varepsilon - 1, (j = 1, 2, 3, \ldots, \tau R1\ )$

$j\varepsilon - 1 - a(n_1 + n_2 + \ldots + n_i), i\in [1, (M - 1)],j \in [\tau(Ri\ )+1, \tau R(\ i+ 1)\ ])$ -(29)

We can get

$\Delta_2(z)=-z_{-\tau}[-z^{(\tau\ +1)} +\varepsilon(z^{\tau} +z^{(\tau\ -1)} +z^{(\tau\ -2)} + \ldots + z)]$

-(30)

From [24], when _ < $1/(\tau + 1)$, all the zeros of (30) lie within the unit disc, and the original network system (2) with the controller (4) is stable.

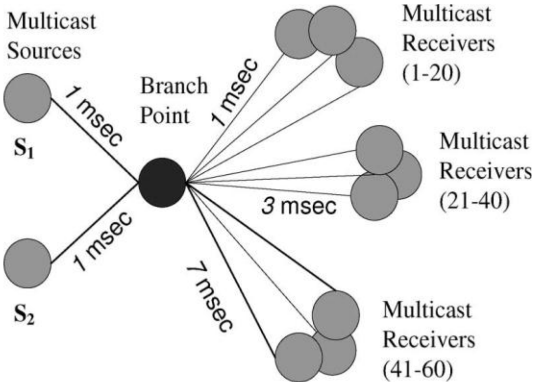

Fig. 2. Multicast simulation model 1.

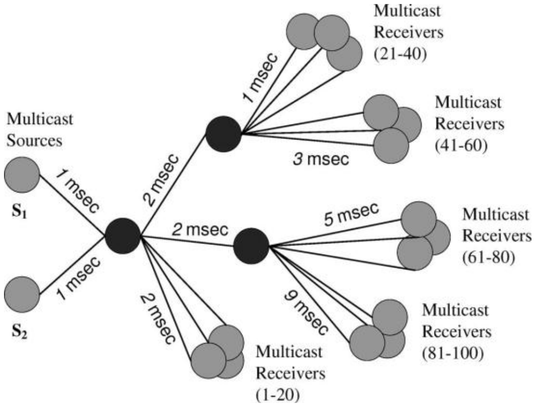

Fig. 3. Multicast system model 2.

5. Performance Evaluation

To evaluate the performance of the studied multicast congestion control scheme, we focus on the following two simulation models, and are mostly interested in analyzing the transient behaviors of the network. In the performance analysis, the duration of response time, receiving rate of receivers, and steady state of buffer occupancy are the main concerns.

From the view of control theory, a control scheme with short response time has the following advantages: when the buffer of receiver nodes is close to the threshold, one may tell the sending node to reduce the sending rate and prevent the loss of packets as soon as possible; while when the available bandwidth increases, the sending node increases the sending rate as soon as possible and enhances the utilization rate of the bandwidth.

5. Conclusion

The advances in MIMO systems and networking technologies introduced a revolution in recent times, which promises significant impact throughout our lives, especially in wireless and wired multicast (multipoint-to-multipoint) transmission field. In this paper, we presented two novel wireless and wired multicast schemes, called SPID and SPI schemes, using an explicit rate feedback mechanism to design a controller for regulating the source rates in wireless and wired multipoint-to-multipoint multicast networks. The control parameters of the SPID and SPI controllers can be designed to ensure the stability of the control loop in terms of buffer occupancy and adjust automatically, depending on the network load. This subsequently means that then schemes provide the least packet loss in steady state. Relevant pseudocodes for implementation have been developed, and the paper shows how the two controllers could be designed to adjust the rates of data service. Simulations have been carried out with wireless and wired multipoint-to-multipoint multicast models to evaluate the performance of the SPID and SPI controllers.

The simulation results clearly demonstrate the efficiency of our scheme in terms of system stability and fast response of the buffer occupancy, as well as controlled sending rates, low packet loss, and high scalability. The simulation results also show that SPID scheme has better performance than SPI scheme; however, SPID scheme requires more computing time and CPU resources. As evident from the analyses and simulation results, the proposed multicast scheme is simple and also can support unicast. We believe that our study is a valuable foundation for a unified flow control scheme capable of being deployed in real multicast networks. A limitation of the explicit rate schemes is that if the network has a larger transfer delay, then the effect of the control schemes becomes weak. A possible reason is that a larger delay makes the response time too long, which is not good for an applicable network. Our further research along this line of study would investigate TCP-friendly related issues in multicast congestion control.

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