LwIP 协议栈分析

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目录

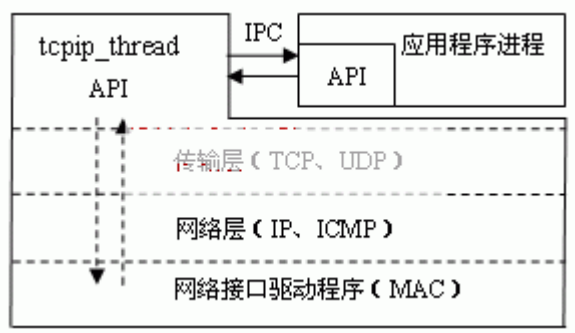
1 简介

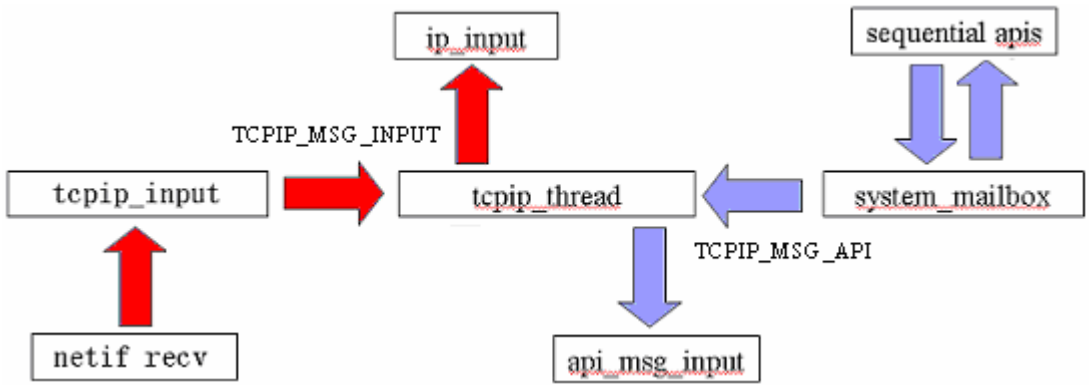
lwIP 是瑞士计算机科学院（Swedish Institute of Computer Science）的 Adam Dunkels 等开发的一套用于嵌入式系统的开放源代码 TCP/IP 协议栈。Lwip 既可以移植到操作系统上，又可以在无操作系统的情况下独立运行.

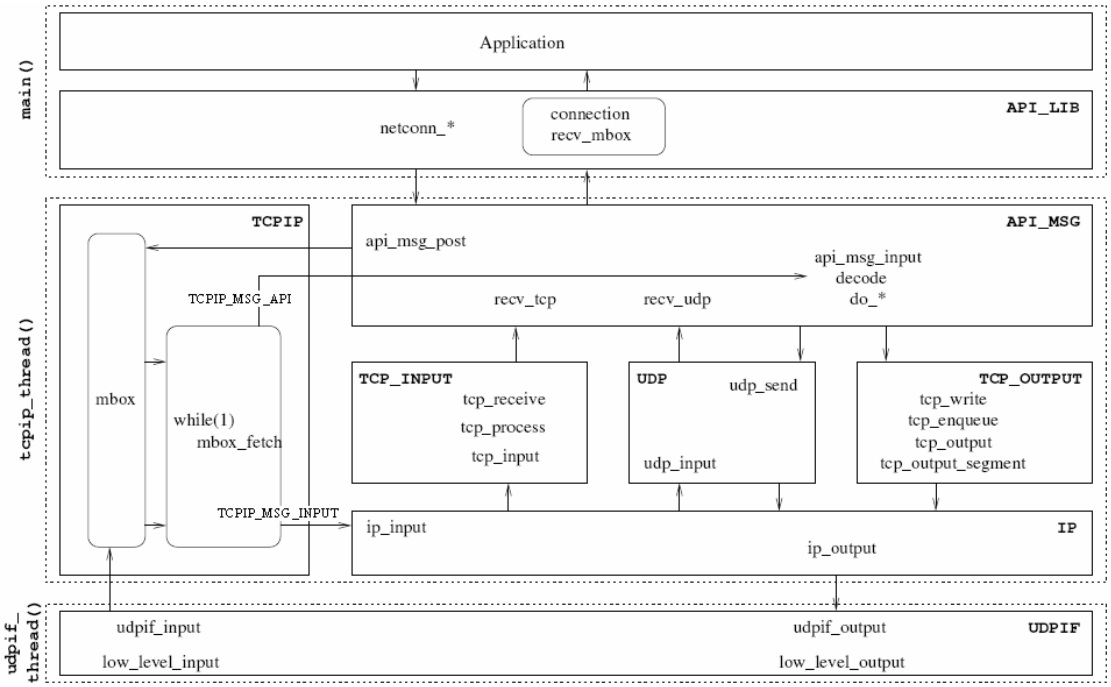
LwIP 的特性如下：

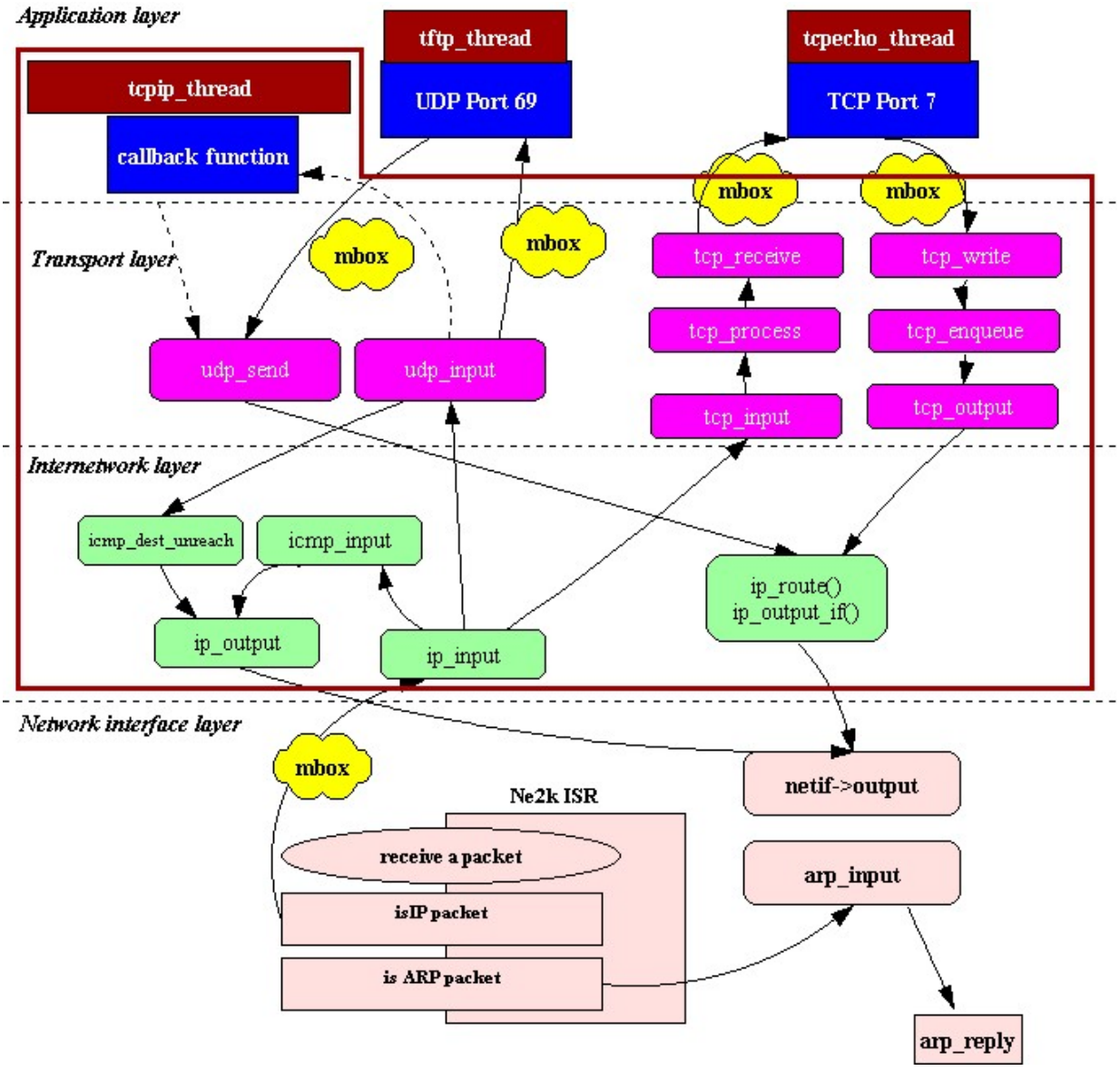
- 支持多网络接口下的 IP 转发
- 支持 ICMP 协议
- 包括实验性扩展的的 UDP（用户数据报协议）
- 包括阻塞控制，RTT 估算和快速恢复和快速转发的 TCP（传输控制协议）
- 提供专门的内部回调接口（Raw API）用于提高应用程序性能
- 可选择的 Berkeley 接口 API（多线程情况下）
- 在最新的版本中支持 ppp
- 新版本中增加了的 IP fragment 的支持.
- 支持 DHCP 协议,动态分配 ip 地址.
- 支持 IPv6

2 Architecture



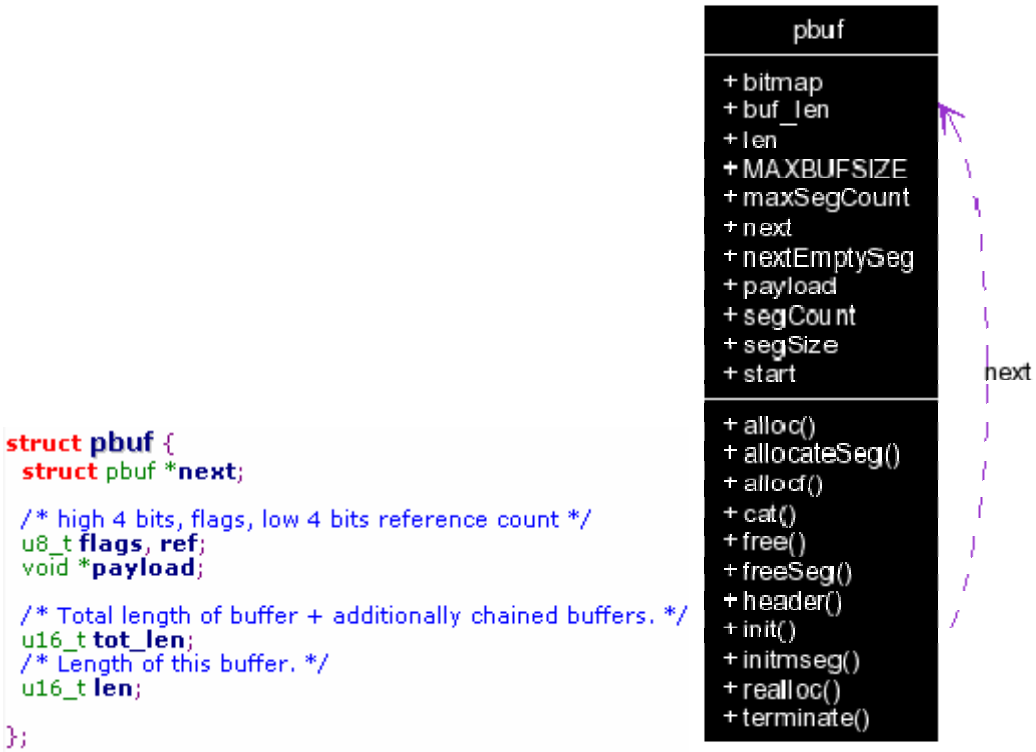


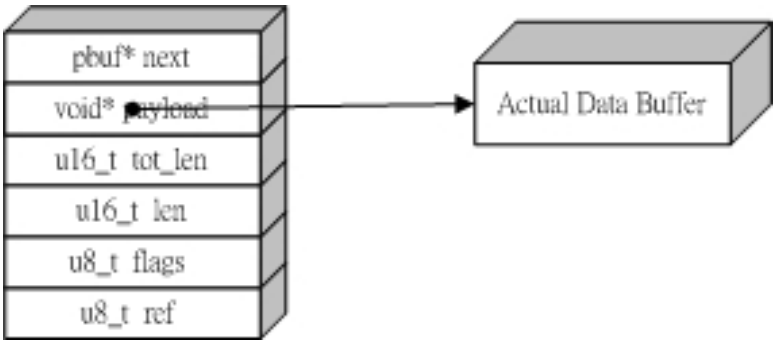

main()
Application
API_LIB
netconn_*
connection
recv_mbox
tcpip_thread()
TCPIP
API_MSG
api_msg_post
api_msg_input
decode
do_*
TCPIP_MSG_API
recv_tcp
recv_udp
mbox
while(1)
mbox_fetch
TCP_INPUT
tcp_receive
tcp_process
tcp_input
UDP
udp_send
udp_input
TCP_OUTPUT
tcp_write
tcp_enqueue
tcp_output
tcp_output_segment
TCPIP_MSG_INPUT
ip_input
IP
ip_output
udpif_thread()
udpif_input
low_level_input
udpif_output
low_level_output
UDPIF


Application layer
tftp_thread
tcpecho_thread
tcpip_thread
UDP Port 69
TCP Port 7
callback function
mbox
mbox
mbox
mbox
Transport layer
tcp_receive
tcp_write
tcp_process
tcp_enqueue
udp_send
udp_input
tcp_input
tcp_output
Internetwork layer
icmp_dest_unreach
icmp_input
ip_route()
ip_output_if()
ip_output
ip_input
Network interface layer
mbox
netif->output
Ne2k ISR
receive a packet
arp_input
isIP packet
is ARP packet
arp_reply

3 数据结构

3.1 Pbuf





Pbuf是lwIP包的内部表示，被设计为最小化栈的特殊需要。Pbufs类似于BSD实现中的mbufs。Pbuf结构支持为包内容动态分配内存和让包数据驻留在静态内存中。Pbufs能被一个称为pbuf链的链接到一个链表中，以至一个包能跨越多个pbufs。

Pbufs 有三种类型:PBUF_RAM,PBUF_ROM 和 PBUF_POOL。图 1 表示 PBUF_RAM 类型，包含有存在内存中由 pbuf 子系统管理的包数据。图 2 显示了一个 pbuf 链表，第 1 个是 PBUF_RAM 类型，第 2 个是 PBUF_ROM 类型，意味着它包含有不被 pubf 子系统管理的内存数据。图 3 描述了 PBUF_POOL，其包含有从固定大小 pbuf 池中分配来的 pbuf。一个 pbuf 链可以包含多个不同类型的 pbuf。

这三种类型有不同的用处。PBUF_POOL类型主要由网络设备驱动使用，因为分配单个pbuf快速且适合中断句柄使用。PBUF_ROM类型由应用程序发送那些在应用程序内存空间中的

数据时使用。这些数据不会在pbuf递交给TCP/IP栈后被修改，因此这个类型主要用于当数据在ROM中时。PBUF_ROM中指向数据的头部被存在链表中其前一个PUBF_RAM类型的pbuf中，如图 2 所示。
PBUF_RAM 类型也用于应用程序发送动态产生的数据。这情况下，pbuf 系统不仅为应用程序数据分配内存，也为将指向（prepend）数据的头部分配内存。如图 1 所示。Pbuf 系统不能预知哪种头部将指向（prepend）那些数据，只假定最坏的情况。头部的大小在编译时确定。

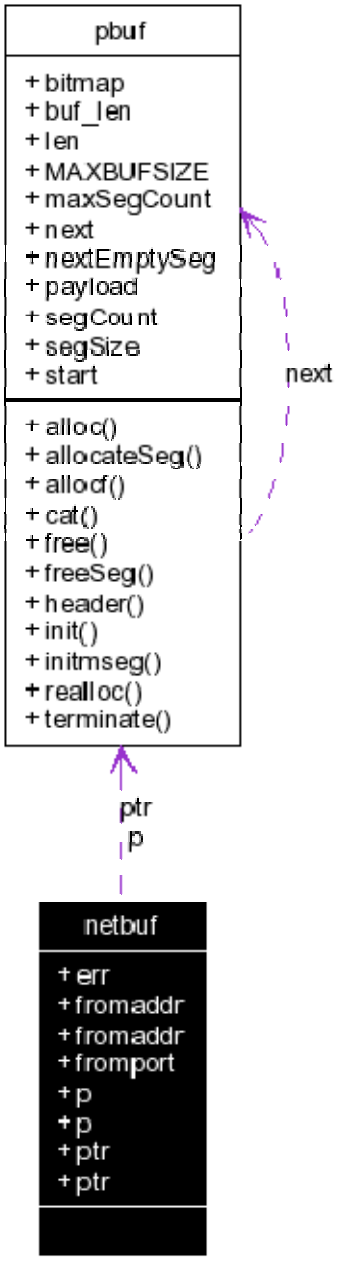
本质上，进来的 pbuf 是 PBUF_POOL 类型，而出去的 pbuf 是 PBUF_ROM 或 PBUF_RAM 类型。

从图 1，图 2 可以看出pbuf的内部结构。Pbuf结构包含有两个指针，两个长度字段，一个标志字段，和一个参考计数。Next字段指向统一链表中的下一个pbuf。有效载荷指针指向该pbuf中数据的起始点。Len字段包含有该pbuf数据内同的长度。Tot_len字段是当前pbuf和所有链表接下来中的len字段值的总和。简单说，tot_len字段是len字段及下一个pbuf中tot_len字段值的总和。Flags字段表示pbuf类型而ref字段包含一个参考计数。Next和payload字段是本地指针，其大小由处理器体系结构决定。两个长度字段是 16 位无符号整数，而flags和ref字段都是 4 比特大小。Pbuf的总大小决定于使用的处理器体系结构。在 32 位指针和 4 字节校正的体系结构上，总大小是 16 字节，而在 16 位指针和 1 自己校正的体系结构上，总大小是 9 字节。

Pbuf模块提供了操作pbuf的函数。Pbuf_alloc()可以分配前面提到的三种类型的pbuf。Pbuf_ref()增加引用计数,pbuf_free()释放分配的空间，它先减少引用计数，当引用计数为 0 时就释放pbuf。Pbuf_realloc()收缩空间以使pbuf只占用刚好的空间保存数据。Pbuf_header()调整payload指针和长度字段，以使一个头部指向pbuf中的数据。Pbuf_chain()和pbuf_dechain()用于链表化pbuf。

3.2 Netbuf

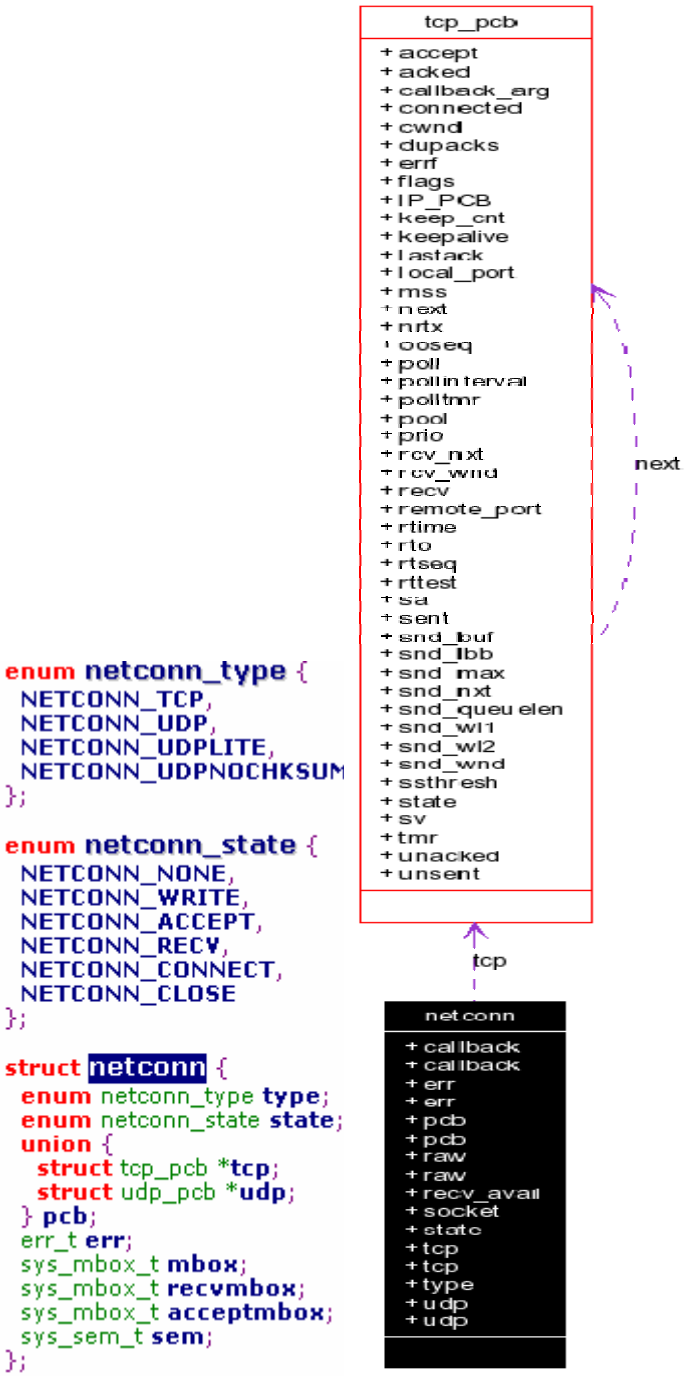
描述网络缓存的数据类型




```
struct netbuf {
  struct pbuf *p, *ptr;
  struct ip_addr *fromaddr;
  u16_t fromport;
  err_t err;
};
```

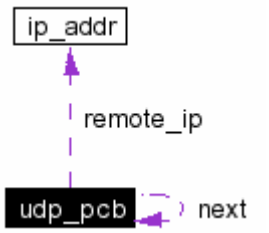
3.3 Netconn

描述网络连接的数据类型
与socket一一对应


tcp_pcb
+ accept
+ acked
+ callback_arg
+ connected
+ cwnd
+ dupacks
+ errf
+ flags
+ IP_PCB
+ keep_cnt
+ keepalive
+ lastack
+ local_port
+ mss
+ next
+ nrtx
+ ooseq
+ poll
+ polinterval
+ polltmr
+ pool
+ prio
+ rcv_nxt
+ rcv_wnd
+ recv
+ remote_port
+ rtime
+ rto
+ rtseq
+ rttest
+ sa
+ sent
+ snd_buf
+ snd_lbb
+ snd_max
+ snd_nxt
+ snd_queuelen
+ snd_wl1
+ snd_wl2
+ snd_wnd
+ ssthresh
+ state
+ sv
+ tmr
+ unacked
+ unsent
next
tcp
netconn
+ callback
+ callback
+ err
+ err
+ pcb
+ pcb
+ raw
+ raw
+ recv_avail
+ socket
+ state
+ tcp
+ tcp
+ type
+ udp
+ udp
enum netconn_type {
NETCONN_TCP,
NETCONN_UDP,
NETCONN_UDPLITE,
NETCONN_UDPNOCHKSUM
};
enum netconn_state {
NETCONN_NONE,
NETCONN_WRITE,
NETCONN_ACCEPT,
NETCONN_RECV,
NETCONN_CONNECT,
NETCONN_CLOSE
};
struct netconn {
enum netconn_type type;
enum netconn_state state;
union {
struct tcp_pcb *tcp;
struct udp_pcb *udp;
} pcb;
err_t err;
sys_mbox_t mbox;
sys_mbox_t recvmbox;
sys_mbox_t acceptmbox;
sys_sem_t sem;
};

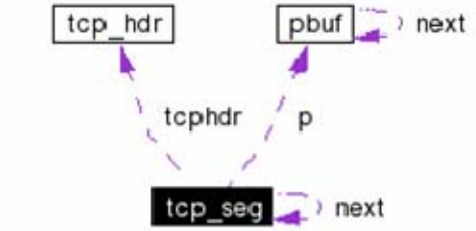
3.4 udp_pcb

```
struct udp_pcb {
  struct udp_pcb *next;

  struct ip_addr local_ip, remote_ip;
  u16_t local_port, remote_port;

  u8_t flags;
  u16_t chksum_len;

  void (* recv)(void *arg, struct udp_pcb *pcb, struct pbuf *p,
          struct ip_addr *addr, u16_t port);
  void *recv_arg;
};
```

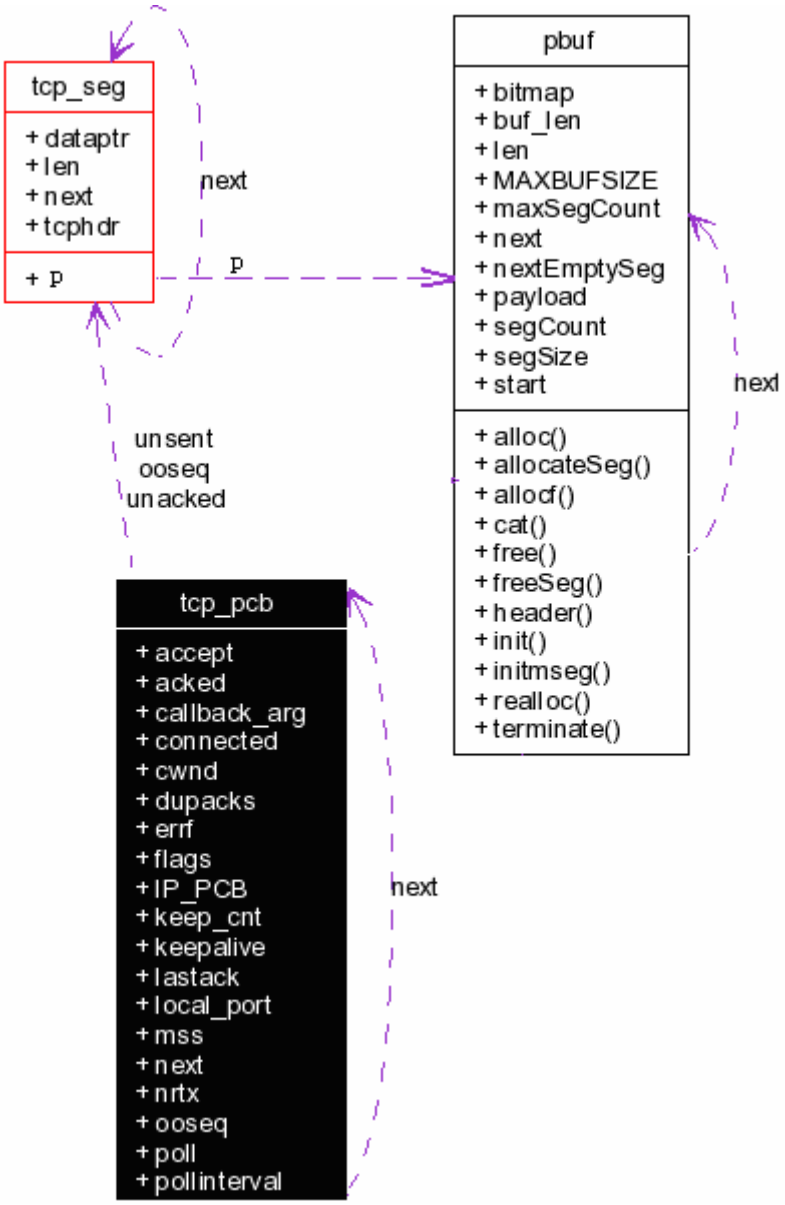


3.5 tcp_seg

```
/* This structure is used to represent TCP segments. */
struct tcp_seg {
  struct tcp_seg *next;/* used when putting segements on a queue*/
  struct pbuf *p;       /* buffer containing data + TCP header */
  void *dataptr;        /* pointer to the TCP data in the pbuf */
  u16_t len;           /* the TCP length of this segment */
  struct tcp_hdr *tcphdr;  /* the TCP header */
};
```



3.6 tcp_pcb

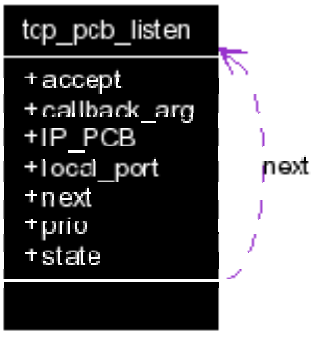

tcp_seg
+ dataptr
+ len
+ next
+ tcphdr
+ p
next
p
unsent
ooseq
unacked
pbuf
+ bitmap
+ buf_len
+ len
+ MAXBUFSIZE
+ maxSegCount
+ next
+ nextEmptySeg
+ payload
+ segCount
+ segSize
+ start
+ alloc()
+ allocateSeg()
+ allocf()
+ cat()
+ free()
+ freeSeg()
+ header()
+ init()
+ initmseg()
+ realloc()
+ terminate()
next
tcp_pcb
+ accept
+ acked
+ callback_arg
+ connected
+ cwnd
+ dupacks
+ errf
+ flags
+ IP_PCB
+ keep_cnt
+ keepalive
+ lastack
+ local_port
+ mss
+ next
+ nrtx
+ ooseq
+ poll
+ pollinterval
next

```
/* the TCP protocol control block */
struct tcp_pcb {
  struct tcp_pcb *next;   /* for the linked list */
  enum tcp_state state;   /* TCP state */
  void *callback_arg;

  /* Function to call when a listener has been connected. */
  err_t (* accept)(void *arg, struct tcp_pcb *newpcb, err_t err);

  struct ip_addr local_ip;
  u16_t local_port;

  struct ip_addr remote_ip;
  u16_t remote_port;

  /* receiver varables */
  u32_t rcv_nxt;   /* next seqno expected */
  u16_t rcv_wnd;   /* receiver window */

  u16_t tmr; /* Timers */
  u8_t rtime; /* Retransmission timer. */
  u16_t mss;   /* maximum segment size */

  u8_t flags;
#define TF_ACK_DELAY 0x01   /* Delayed ACK. */
#define TF_ACK_NOW   0x02   /* Immediate ACK. */
#define TF_INFR      0x04   /* In fast recovery. */
#define TF_RESET     0x08   /* Connection was reset. */
#define TF_CLOSED    0x10   /* Connection was sucessfully closed. */
#define TF_GOT_FIN   0x20   /* Connection was closed by the remote end. */

  /* RTT estimation variables. */
  u16_t rttest; /* RTT estimate in 500ms ticks */
  u32_t rtseq;  /* sequence number being timed */
  s32_t sa, sv;

  u16_t rto;    /* retransmission time-out */
  u8_t nrtx;    /* number of retransmissions */

  /* fast retransmit/recovery */
  u32_t lastack; /* Highest acknowledged seqno. */
  u8_t dupacks;
```

```
  /* congestion avoidance/control variables */
  u16_t cwnd;
  u16_t ssthresh;

  /* sender variables */
  u32_t snd_nxt,      /* next seqno to be sent */
    snd_max,      /* Highest seqno sent. */
    snd_wnd,      /* sender window */
    snd_wl1, snd_wl2,
    snd_lbb;

  u16_t snd_buf;   /* Avaliable buffer space for sending. */
  u8_t snd_queuelen;

  /* Function to be called when more send buffer space is avaliable. */
  err_t (* sent)(void *arg, struct tcp_pcb *pcb, u16_t space);
  u16_t acked;
  /* Function to be called when (in-sequence) data has arrived. */
  err_t (* recv)(void *arg, struct tcp_pcb *pcb, struct pbuf *p, err_t err);
  struct pbuf *recv_data;
  /* Function to be called when a connection has been set up. */
  err_t (* connected)(void *arg, struct tcp_pcb *pcb, err_t err);
  /* Function which is called periodically. */
  err_t (* poll)(void *arg, struct tcp_pcb *pcb);
  /* Function to be called whenever a fatal error occurs. */
  void (* errf)(void *arg, err_t err);

  u8_t polltmr, pollinterval;

  /* These are ordered by sequence number: */
  struct tcp_seg *unsent;   /* Unsent (queued) segments. */
  struct tcp_seg *unacked;  /* Sent but unacknowledged segments. */
#if TCP_QUEUE_OOSEQ
  struct tcp_seg *ooseq;    /* Received out of sequence segments. */
#endif /* TCP_QUEUE_OOSEQ */
} ? end tcp_pcb ? ;
```

3.7 tcp_pcb_listen

```
struct tcp_pcb_listen {
  struct tcp_pcb_listen *next;   /* for the linked list */

  enum tcp_state state;   /* TCP state */

  void *callback_arg;

  /* Function to call when a listener has been connected. */
  void (* accept)(void *arg, struct tcp_pcb *newpcb);

  struct ip_addr local_ip;
  u16_t local_port;
};
```



3.8 Mbox

```
struct sys_mbox {
  u16_t first, last;
  void *msgs[SYS_MBOX_SIZE];
  struct sys_sem *mail;
  struct sys_sem *mutex;
};
```

3.8.1 tcpip_msg

```
enum tcpip_msg_type {
  TCPIP_MSG_API,
  TCPIP_MSG_INPUT
};

struct tcpip_msg {
  enum tcpip_msg_type type;
  sys_sem_t *sem;
  union {
    struct api_msg *apimsg;
    struct {
      struct pbuf *p;
      struct netif *netif;
    } inp;
  } msg;
};
```

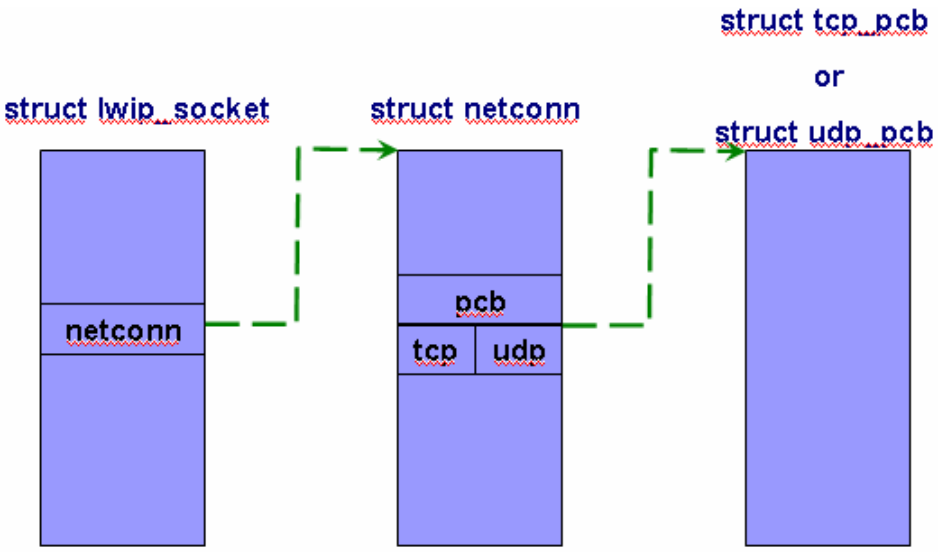
TCPIP_MSG_API 表示从 API (上层)来的包,包括 api_msg 中的 api_msg_type 所有类型的包;
TCPIP_MSG_INPUT 表示从 IP(下层)来的包.

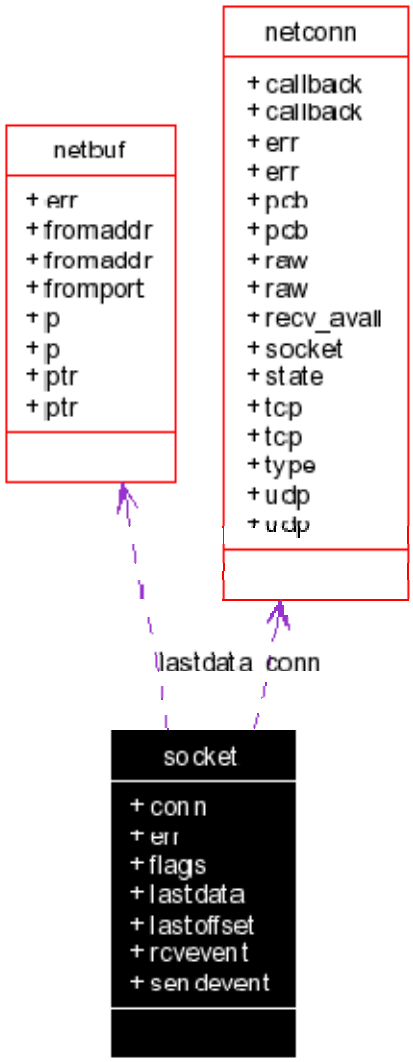
3.8.2 api_msg

```
enum api_msg_type {
  API_MSG_NEWCONN,
  API_MSG_DELCONN,
  API_MSG_BIND,
  API_MSG_CONNECT,
  API_MSG_LISTEN,
  API_MSG_ACCEPT,
  API_MSG_SEND,
  API_MSG_RECV,
  API_MSG_WRITE,
  API_MSG_CLOSE,
  API_MSG_MAX
};

struct api_msg_msg {
  struct netconn *conn;
  enum netconn_type conntype;
  union {
    struct pbuf *p;
    struct {
      struct ip_addr *ipaddr;
      u16_t port;
    } bc;
    struct {
      void *dataptr;
      u16_t len;
      unsigned char copy;
    } w;
    sys_mbox_t mbox;
    u16_t len;
  } msg;
};

struct api_msg {
  enum api_msg_type type;
  struct api_msg_msg msg;
};
```

3.9 Socket

```
struct lwip_socket {
  struct netconn *conn;
  struct netbuf *lastdata;
  u16_t lastoffset;
};

static struct lwip_socket sockets[NUM_SOCKETS];
```





3.10 定时

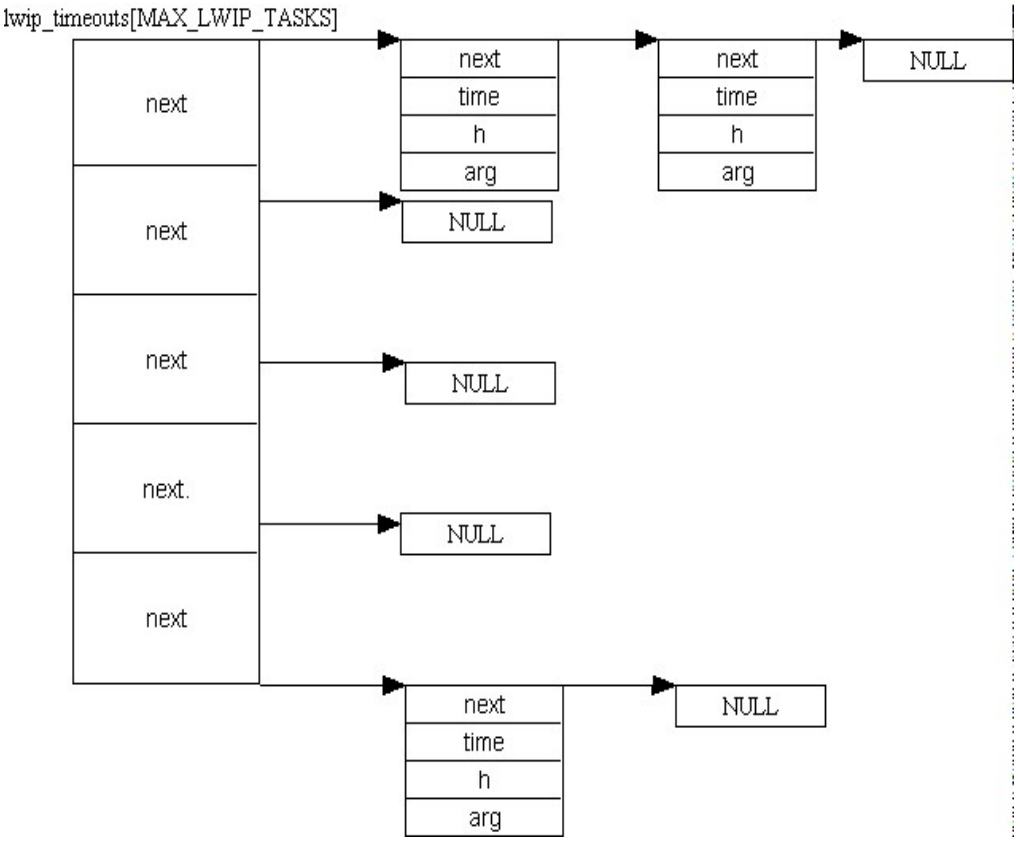
```
struct sys_timeout {
  struct sys_timeout *next;
  u16_t time;
  sys_timeout_handler h;
  void *arg;
};

struct sys_timeouts {
  struct sys_timeout *next;
};
```

在 tcp/ip 协议中很多时候都要用到定时,定时的实现也是 tcp/ip 协议栈中一个重要的部分.lwip 中定时事件的数据结构如下.

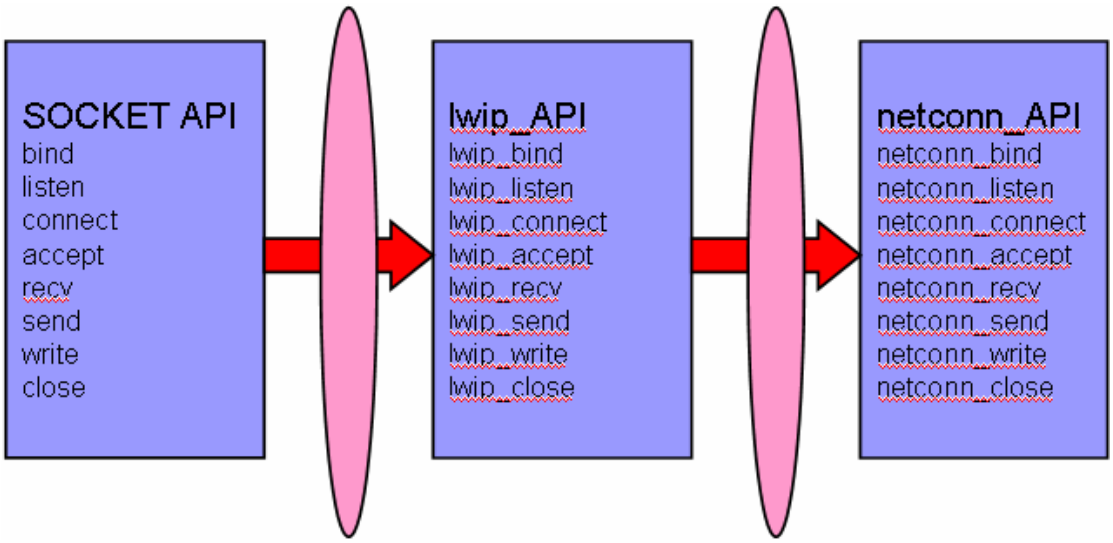
struct sys_timeout {
  struct sys_timeout *next;//指向下一个定时结构
  u32_t time;//定时时间
  sys_timeout_handler h;//定时时间到后执行的函数
  void *arg;//定时时间到后执行函数的参数.
};

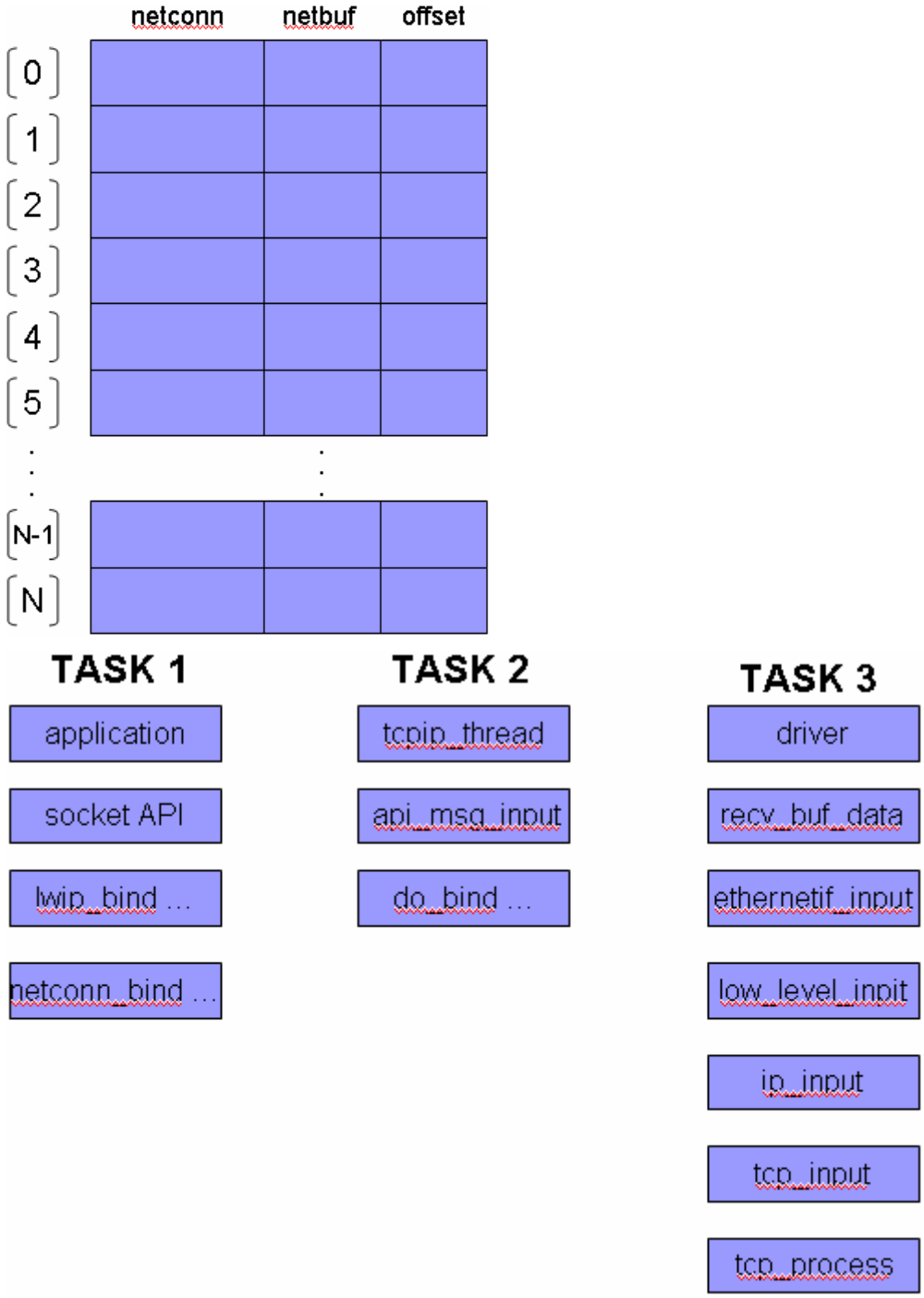
```
struct sys_timeouts {
  struct sys_timeout *next;
};
struct sys_timeouts lwip_timeouts[LWIP_TASK_MAX];
```

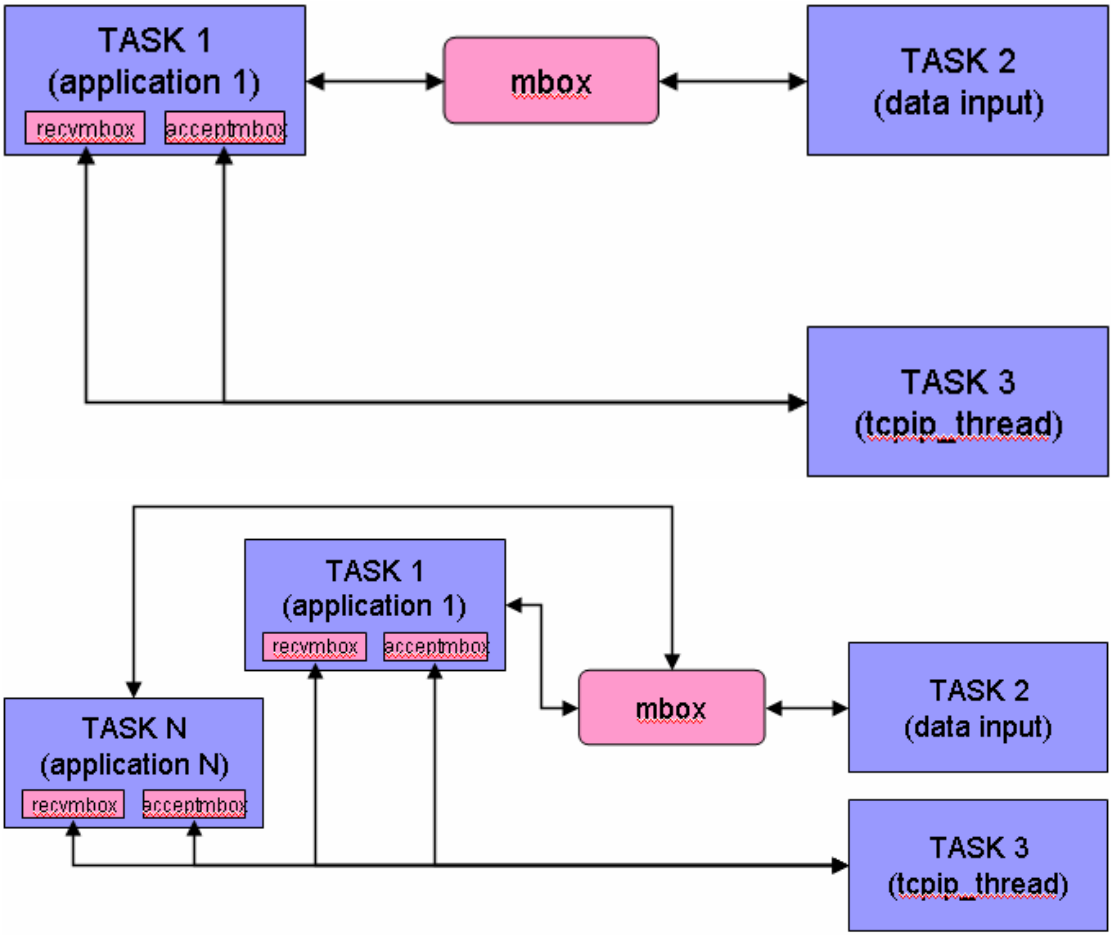
Lwip 中的定时事件表的结构如下图,每个和 tcp/ip 相关的任务的一系列定时事件组成一个单向链表.每个链表的起始指针存在 lwip_timeouts 的对应表项中.



4 API

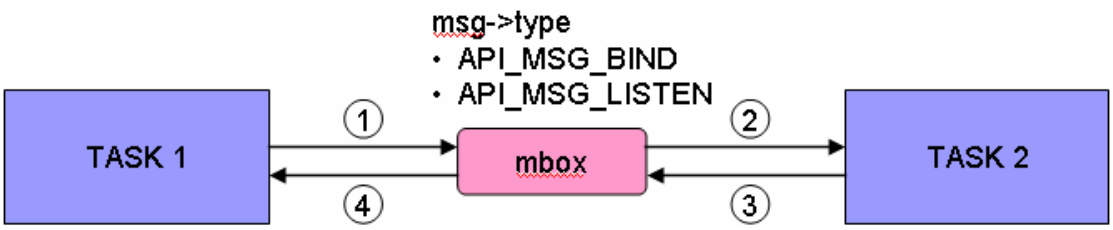



netconn
netbuf
offset
0
1
2
3
4
5
N-1
N
TASK 1
application
socket API
lwip_bind ...
netconn_bind ...
TASK 2
tcpip_thread
api_msg_input
do_bind ...
TASK 3
driver
recv_buf_data
ethernetif_input
low_level_input
ip_input
tcp_input
tcp_process



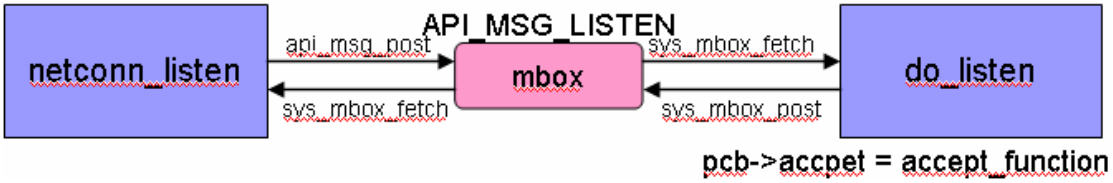
- TYPE 1
  - BIND, LISTEN, CLOSE
- TYPE 2
  - CONNECT
- TYPE 3
  - SEND. WRITE
- TYPE 4
  - ACCEPT, RECV

4.1 TYPE 1

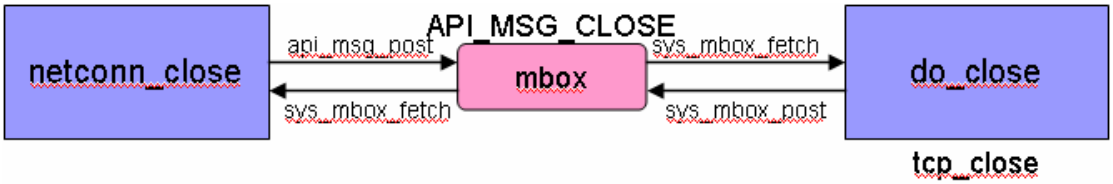


4.1.1 netconn_bind

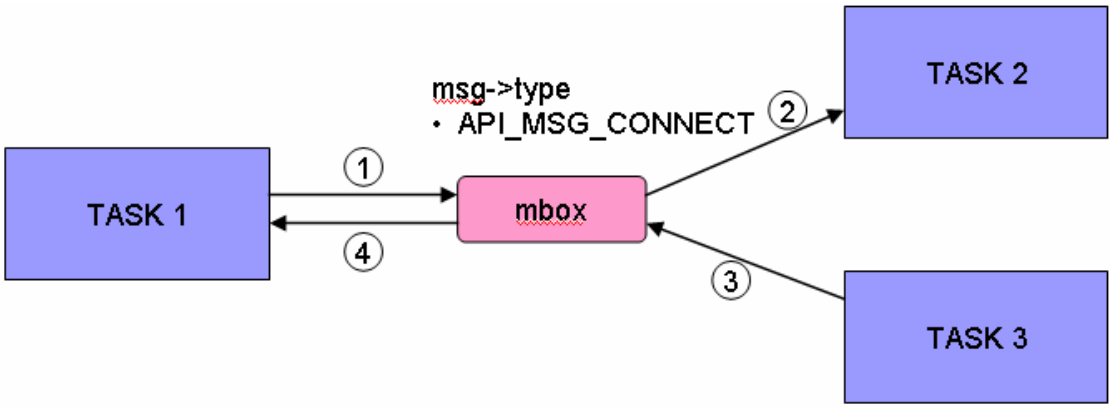
4.1.2 netconn_listen



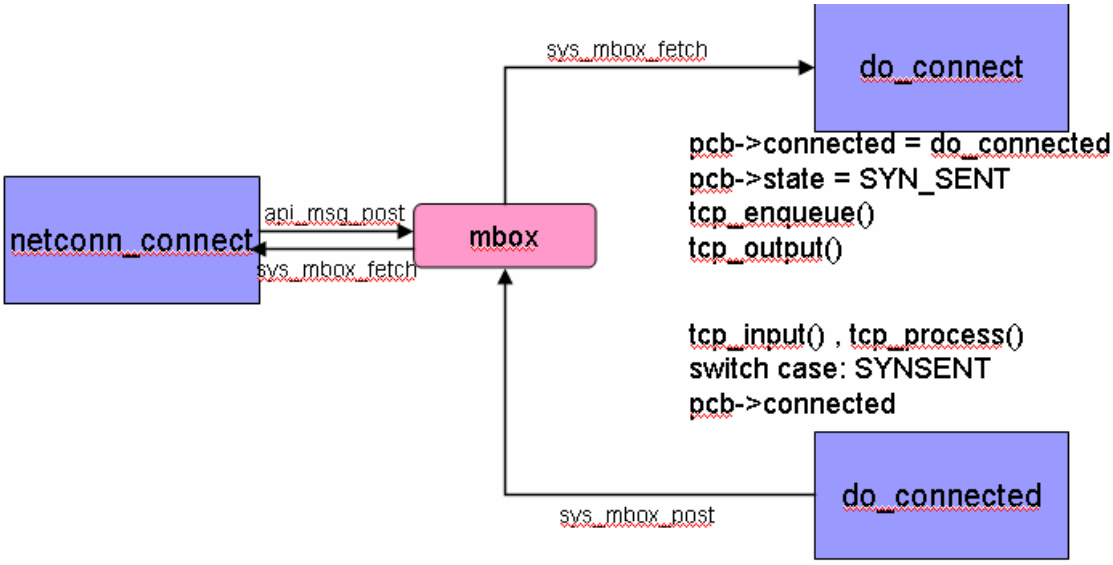
4.1.3 netconn_close



4.2 TYPE 2



4.2.1 netconn_connect



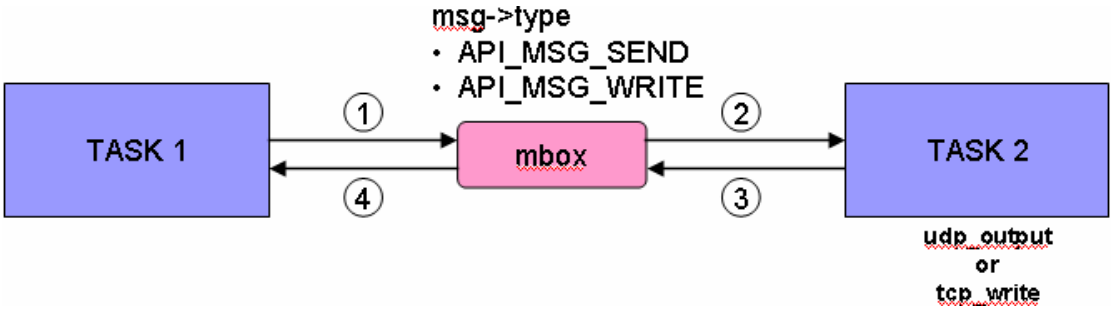
在 lwip 实现中，应用层调用 connect 函数进行主动连接，在该函数内部实际上是生成一个消息发送给 tcpip_thread 线程，在此消息里包含了 conn->mbox 信号量句柄，然后，该函数阻塞等待在此信号量上。一旦底层完成三次握手，连接成功，就会触发 TCP 已连接事件 TCP_EVENT_CONNECTED 回调 do_connect 释放此信号量，connect 随即退出阻塞。在应用层看来，connect 一直阻塞到连接成功，如果不成功就返回-1。

connect 运行在用户线程，实际连接运行在 tcpip_thread 线程，通过消息回调，使两个不同线程的函数建立了同步关系，虽然 TCP 协议时延动态范围很大，达到秒级，但这种消息驱动机制能很好地适应变化。

```
err_t
netconn_connect(struct netconn *conn, struct ip_addr *addr,
           u16_t port)
{
      struct api_msg *msg;

      if(conn == NULL)
        return ERR_VAL;

      if(conn->recvmbox == SYS_MBOX_NULL)
      {
            if((conn->recvmbox = sys_mbox_new()) == SYS_MBOX_NULL)
              return ERR_MEM;
      }

      if((msg = memp_mallocp(MEMP_API_MSG)) == NULL)
          return ERR_MEM;

      msg->type = API_MSG_CONNECT;
      msg->msg.conn = conn;
      msg->msg.msg.bc.ipaddr = addr;
      msg->msg.msg.bc.port = port;
      api_msg_post(msg);

      /*阻 塞 等 待 do_connect释 放 此 信 号 量 */
      sys_mbox_fetch(conn->mbox, NULL);
      /*释 放 msg */
      memp_freep(MEMP_API_MSG, msg);

      return conn->err;
} ? end netconn_connect ?
```

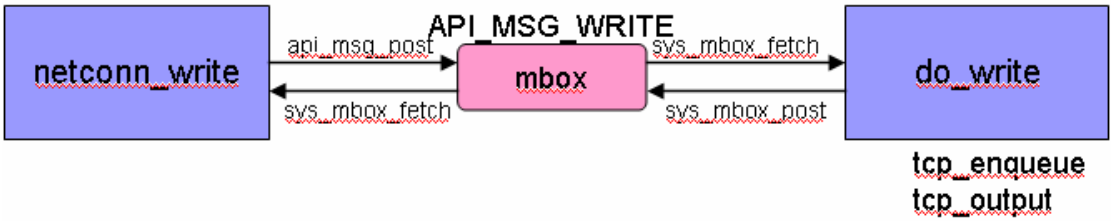
```
static err_t do_connected(void *arg, struct tcp_pcb *pcb, err_t err)
{
        struct netconn *conn;

        conn = arg;

        if(conn == NULL)
          return ERR_VAL;

        conn->err = err;

        if(conn->type == NETCONN_TCP && err == ERR_OK)
            setup_tcp(conn);

        /*释 放 信 号 量 ,返 回 netconn_connect */
        sys_mbox_post(conn->mbox, NULL);
        return ERR_OK;
}
```

4.3 TYPE 3

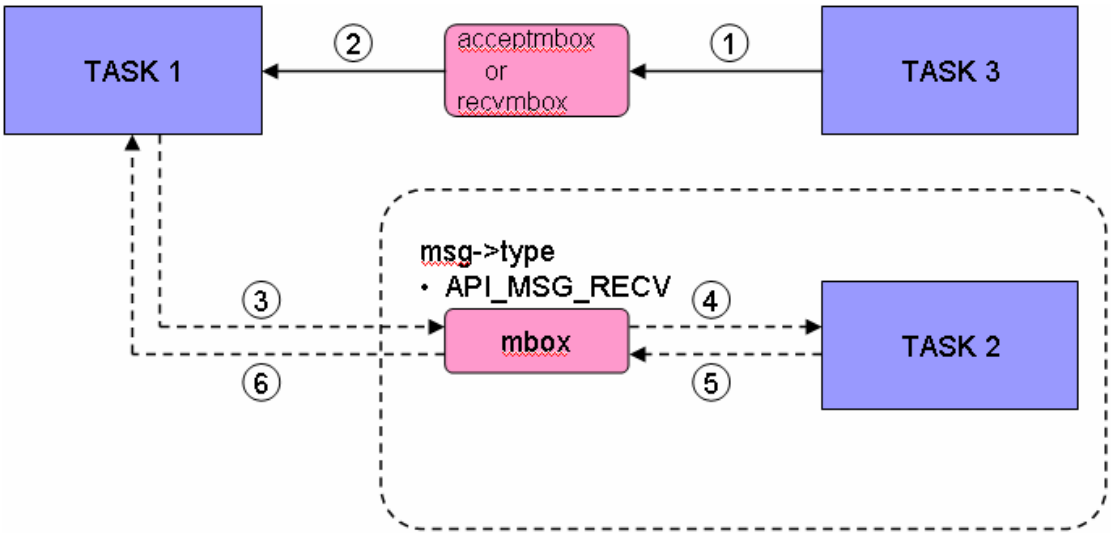


4.3.1 netconn_send

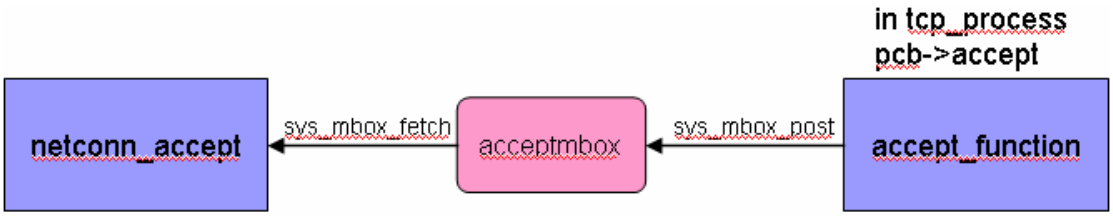
4.3.2 netconn_write



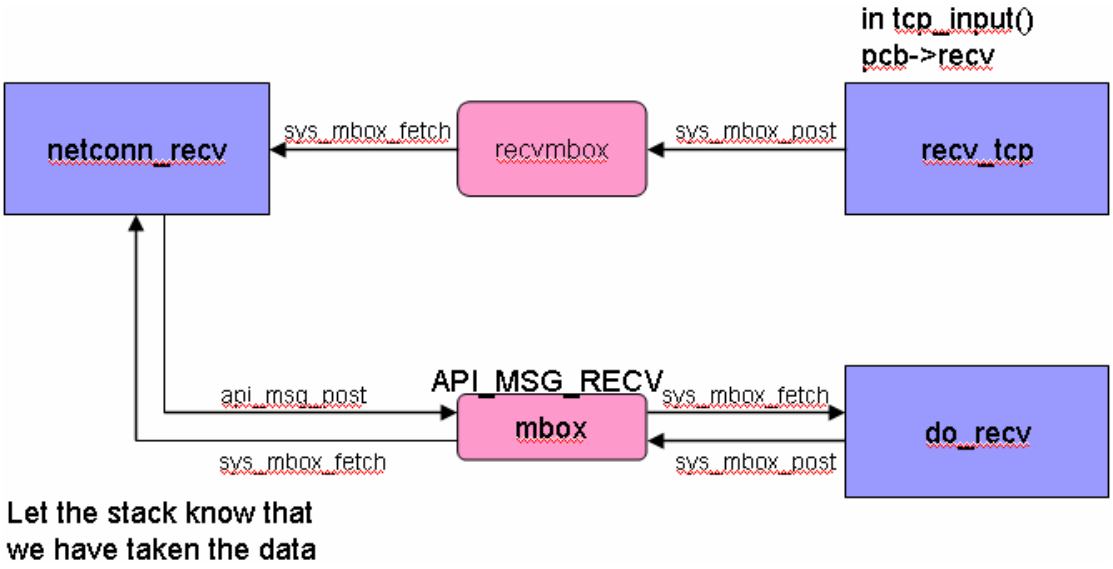
4.4 TYPE 4



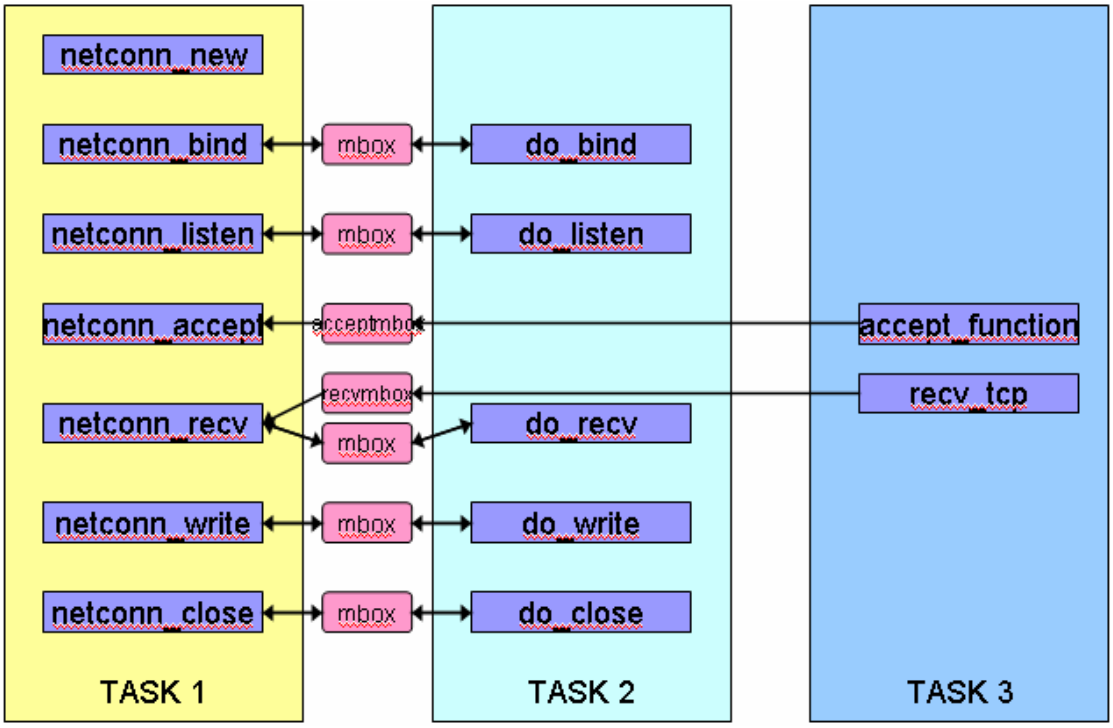
4.4.1 netconn_accept



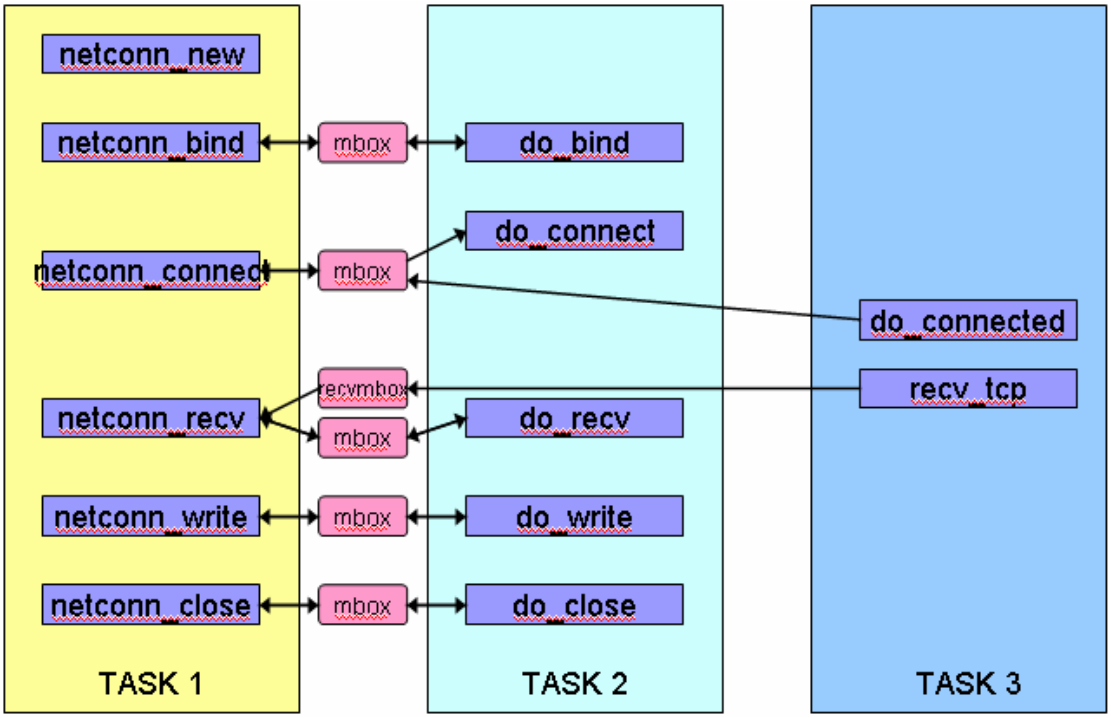
4.4.2 netconn_recv



4.5 Server

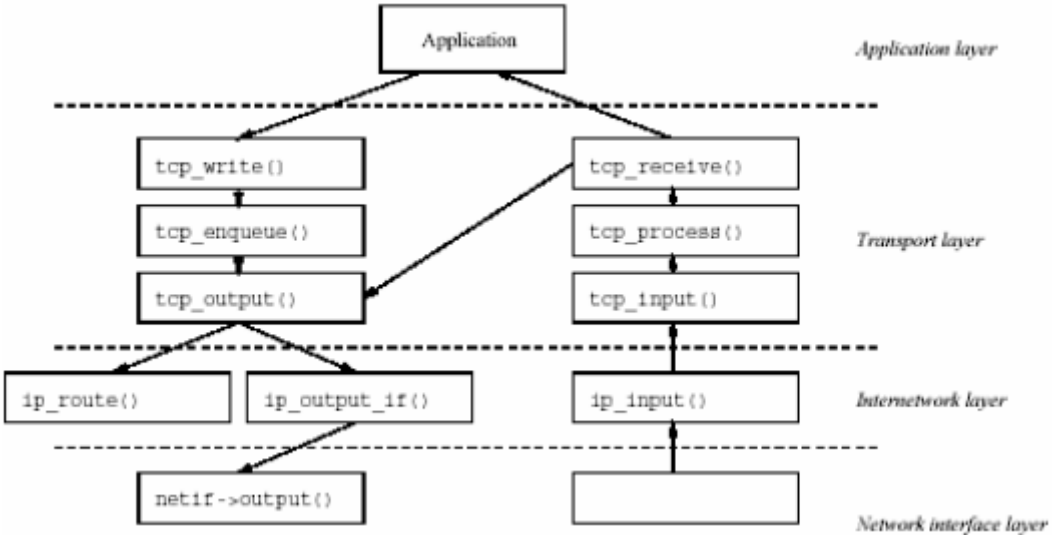


4.6 Client

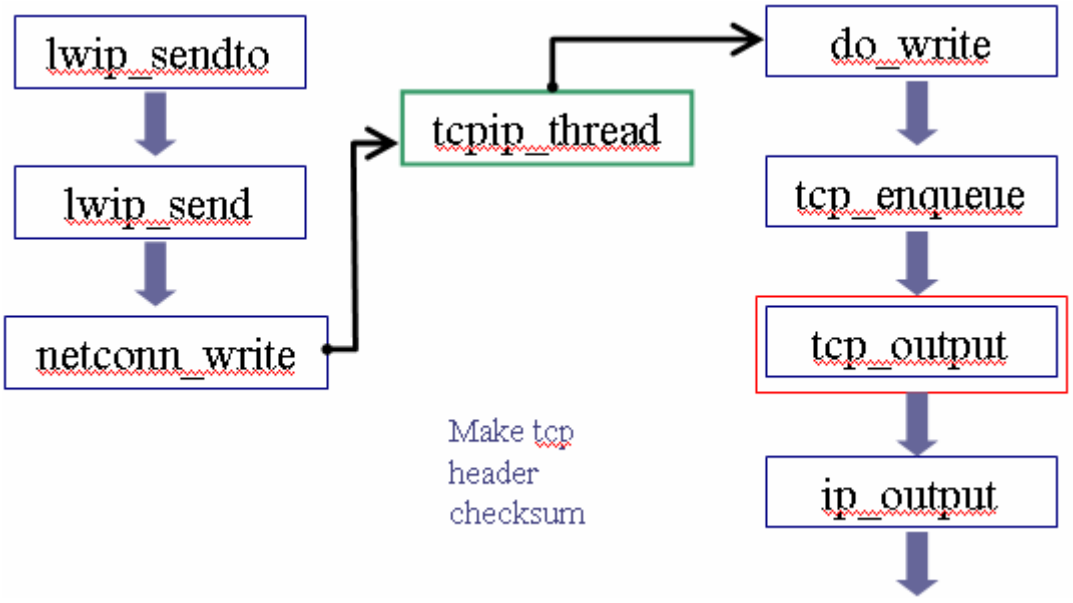


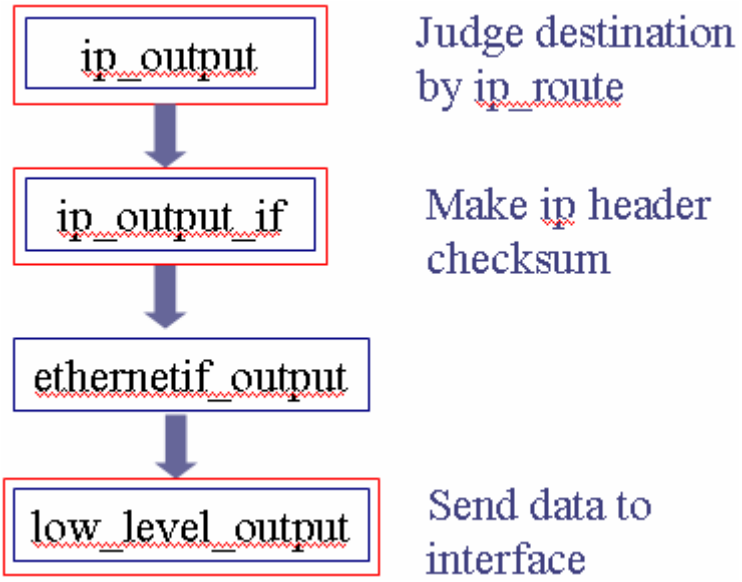
5 流程

5.1 TCP

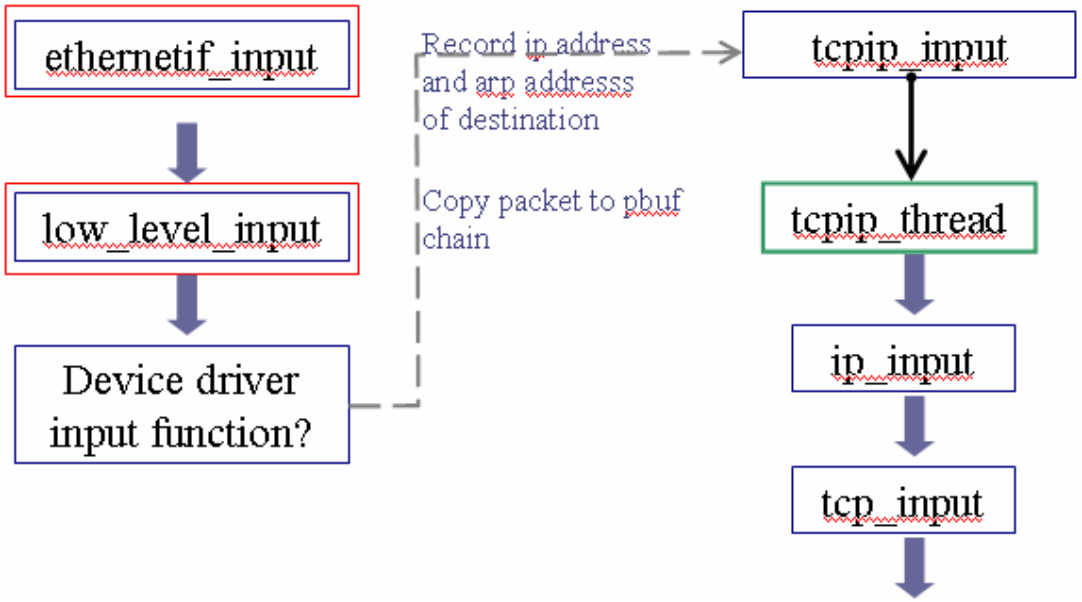


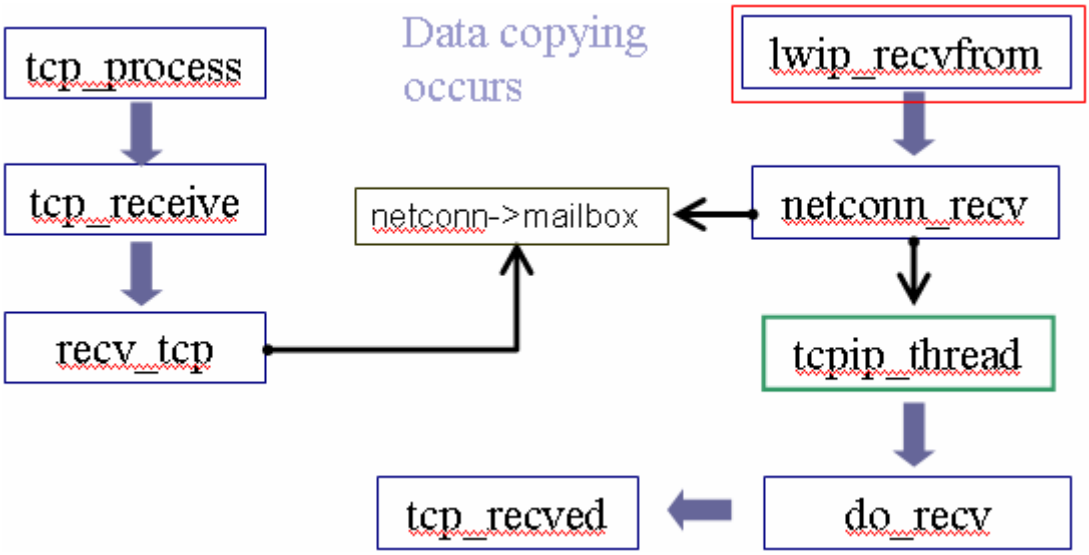
5.1.1 TCP Send



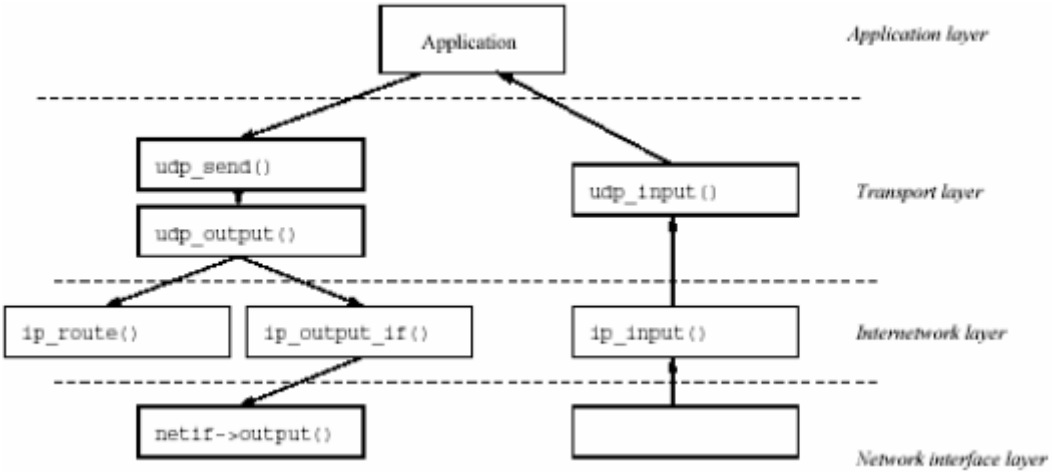


5.1.2 TCP Receive





5.2 UDP



6 主线程

tcpip_thread 是 LwIP 的主线程，整个 tcp/ip 协议栈都在同一个任务(tcpip_thread)中.

```
static void
tcpip_thread(void *arg)
{
  struct tcpip_msg *msg;

  ip_init();
  udp_init();
  tcp_init();

  sys_timeout(TCP_TMR_INTERVAL, (sys_timeout_handler)tcpip_tcp_timer, NULL);

  if(tcpip_init_done != NULL) {
    tcpip_init_done(tcpip_init_done_arg);
  }

  while(1) {                          /* MAIN Loop */
    sys_mbox_fetch(mbox, (void *)&msg);
    switch(msg->type) {
    case TCPIP_MSG_API:
      DEBUGF(TCPIP_DEBUG, ("tcpip_thread: API message %p\n", msg));
      api_msg_input(msg->msg.apimsg);
      break;
    case TCPIP_MSG_INPUT:
      DEBUGF(TCPIP_DEBUG, ("tcpip_thread: IP packet %p\n", msg));
      ip_input(msg->msg.inp.p, msg->msg.inp.netif);
      break;
    default:
      break;
    }
    memp_freep(MEMP_TCPIP_MSG, msg);
  }
} ?  end tcpip_thread ?
```